2012 overview

puget sound marine waters

climate & weather

ocean acidification

dissolved oxygen

water quality

harmful algae

pathogens

shellfish

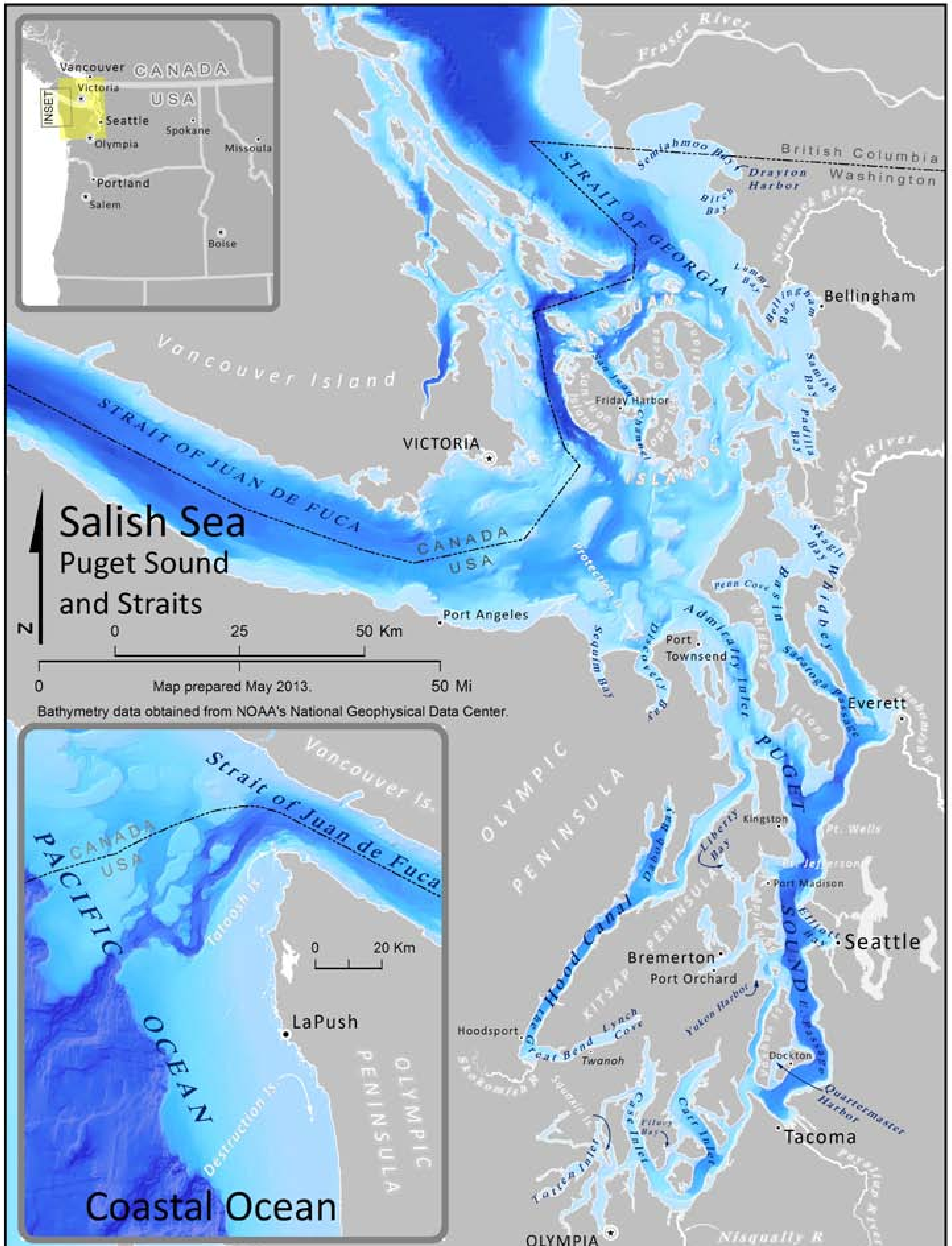
bacteria

birds

NOAA FISHERIES

PSEMP

Puget Sound Ecosystem Monitoring Program



2012
overview

puget sound marine waters

Editors: Stephanie Moore, Kimberle Stark, Julia Bos, Paul Williams, Jan Newton and Ken Dzinbal

Produced by: NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workgroup

About PSEMP:

The Puget Sound Ecosystem Monitoring Program (PSEMP) is a collaboration of monitoring professionals, researchers, and data users from federal, tribal, state, and local government agencies, universities, non-governmental organizations, watershed groups, businesses, and private and volunteer groups.

The objective of PSEMP is to create and support a collaborative, inclusive, and transparent approach to regional monitoring and assessment that builds upon and facilitates communication among the many monitoring programs and efforts operating in Puget Sound. PSEMP's fundamental goal is to assess progress towards the recovery of the health of Puget Sound.

The Marine Waters Workgroup is one of several technical workgroups operating under the PSEMP umbrella – with a specific focus on the inland marine waters of Puget Sound and the greater Salish Sea, including the oceanic, atmospheric, and terrestrial influences and drivers affecting the Sound. For more information about PSEMP and the Marine Waters Workgroup, please visit: https://sites.google.com/a/psemp.org/psemp/.

Introduction

This report provides an overview of 2012 water quality and conditions and associated biota in Puget Sound from comprehensive monitoring and observing programs. The report focuses on the marine waters of greater Puget Sound. Additional selected conditions are also included due to their influence on Puget Sound waters, such as selected climate indices and conditions along the outer Washington coast. In addition to observations on marine phytoplankton, bacteria, and pathogens contained within the marine waters, this year we have expanded to include observations on marine birds that use this marine water habitat.

The objective of this report is to collate and distribute the valuable physical, chemical, and biological information obtained from various marine monitoring and observing programs in Puget Sound. Based on mandate, need, opportunity, and expertise, these efforts employ different approaches and tools that cover various temporal and spatial scales. For example, surface surveys yield good horizontal spatial coverage, but lack depth information; regular station occupation over time identifies long-term trends, but can miss shorter term variation associated with important environmental events; moorings with high temporal resolution describe shorter term dynamics, but have limitations in their spatial coverage. However, collectively, the information representing various temporal and spatial scales can be used to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters. By identifying and connecting trends, anomalies and processes from each of the monitoring programs, this report adds significant and timely value to the individual datasets and enhances our understanding of this complex ecosystem. We present here that collective view for the year 2012.

The data and interpretations presented here are the proceedings of an annual effort by the PSEMP Marine Waters Work Group to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All sections of this report were individually authored. Contact names and website links to more detailed information and data are provided for each contribution. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a synopsis in the Executive Summary that is based on all of the individual contributions and describes the overall trends and drivers of variability and change in Puget Sound's marine waters for 2012.

The larger picture that emerges from this report helps the PSEMP Marine Waters Workgroup to (i) develop an inventory of the current monitoring programs in Puget Sound and conduct a gap analysis to determine how well these programs are meeting priority needs; (ii) update and expand the monitoring results reported in the Puget Sound Vital Sign indicators (http://www.psp.wa.gov/vitalsigns/index.php); and (iii) improve transparency, data sharing, and timely communication of relevant monitoring programs across participating entities. The Northwest Association of Networked Ocean Observing Systems (NANOOS), the regional arm of the U.S. Integrated Ocean Observing System (IOOS) for the Pacific Northwest, is working to increase regional access to marine data. Much of the marine data presented here and an inventory of monitoring assets can be found through the NANOOS web portal (http://www.nanoos.org).

The Canadian ecosystem report "The State of the Ocean for the Pacific North Coast Integrated Management Area" (http://www.dfo-mpo.gc.ca/science/coe-cde/soto/Pacific-North-eng.asp), encompasses approximately 102,000 km² from the edge of the continental shelf east to the British Columbia mainland and includes large portions of the Salish Sea. The annual report provides information that is also relevant for Puget Sound and is a recommended source of complementary information to this report.

Field work near the ORCA buoy deployed near Twanoh in southern Hood Canal. Photo credit: Robert Hubley.

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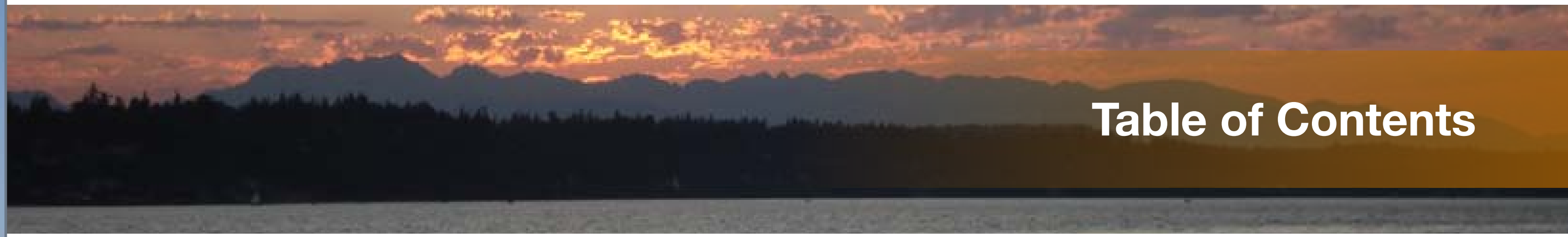

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Executive Summary

From the editors: *The collective view of Puget Sound's marine water environment and some of its associated biota in 2012 is presented here in the context of factors that drive variation, such as large-scale climate patterns, coastal upwelling, and regional weather. It is important to document and understand regional drivers and patterns so that water quality data may be interpreted with these variations in mind, to better attribute human effects versus natural variations and change. We show the conditions from a variety of observations and approaches in order to derive a general overview of the year 2012. A concise summary follows.*

The transition from strong La Niña to ENSO-neutral conditions in early 2012 combined with a continuation of the cool Pacific Decadal Oscillation (PDO) phase was expected to produce colder than usual coastal ocean temperatures and a wetter than usual winter. The North Pacific Gyre Oscillation (NPGO) continued a 6-year positive phase and was expected to provide nutrient-rich waters as boundary condition to Puget Sound. The offshore data series at La Push is not yet long enough for evaluating these large-scale climate patterns, but sea surface temperatures were generally cooler in May through June 2012 compared to 2011. Consistent with these larger scale climate patterns, the spring of 2012 was unusually cool and rainy and affected several ecosystem attributes in Puget Sound. Cooler than normal spring air temperatures and higher than normal river flow discharges resulted in colder and fresher water column conditions. Despite the cool weather, the timing of the spring phytoplankton bloom was typical in early April at many locations throughout the Sound and earlier (February) in southern Hood Canal. The spring bloom was large compared to previous years. Dissolved oxygen (DO) levels increased following both the large spring and fall phytoplankton blooms. The cold water temperatures observed over much of 2012, particularly for deeper waters, also contributed to the relatively high DO values observed in 2012.

The effects of the unusually warm and dry period from August through early October were also discernible in Puget Sound's marine waters. During this period, air temperatures were almost a degree (Celsius) above normal and precipitation was almost entirely absent. River flows were lower than normal and surface waters in the San Juan Channel, Strait of Juan de Fuca, the Main Basin, and Carr Inlet were warmer than normal. A sharper than normal drop in the diatom phytoplankton component during August and September was observed. In addition, an unusually large September phytoplankton bloom occurred throughout much of Puget Sound, which resulted in reduced surface nitrate concentrations (considerably below normal) and elevated DO values in surface waters. Cell counts for the dinoflagellate, *Alexandrium* spp., were low or absent at most the sampled sites in 2012; however, cell counts reached peak levels at three locations in August and September during this anomalous dry period. Paralytic Shellfish Poisoning (PSP) toxins were higher in 2012 than in 2011 and nine PSP-related illnesses were reported from mussels consumed in August and September.

This brief synopsis describes patterns in water quality variables and phytoplankton observed during 2012 and their association with large-scale ocean and climate variations and weather factors. The data compilation and analysis presented in the annual "Puget Sound Marine Water Overview", which began in 2011, offers the opportunity to evaluate the strength of these relationships over time and is a goal of the PSEMP Marine Waters Workgroup. We hope to investigate relationships between other components of the pelagic marine food web, such as zooplankton, fish, seabirds, and marine mammals; such analysis was not possible at this time.

Large-scale climate variability and wind patterns:

- El Niño-Southern Oscillation (ENSO):
  - » La Niña persisted from 2011 into 2012 and transitioned to ENSO-neutral conditions in May 2012. These conditions continued through July and August 2012. From September to December 2012, the Pacific Ocean exhibited borderline ENSO-neutral/weak El Niño conditions.
- Pacific Decadal Oscillation (PDO):
  - » The PDO was negative and variable from January 2012 through spring 2012, but intensified through the summer into August when extremely negative values were reached (-1.93). The PDO was strongly negative during winter 2012. This resulted in cooler than normal water temperatures in Puget Sound in 2012.
- North Pacific Gyre Oscillation (NPGO):
  - » The NPGO index remained high and continued a 6-year positive phase that provided nutrient-rich and highly productive waters as an ocean boundary condition to Puget Sound.
- Upwelling index:
  - » The upwelling index was generally normal for 2012, with the exception of strong downwelling in March and April, and slightly weaker upwelling in June.

Local climate and weather:

- Unusually cool and rainy conditions prevailed through the first half of 2012 into July, followed by a brief, intense period of abnormally warm, dry, sunny weather from August into early October. From mid-October through the end of the year, conditions returned to near-normal.
- Solar radiation (i.e., sunlight) was generally lower than normal in 2012, with the exception of late summer (mid-July through early October) when it was sunnier than normal.

Coastal ocean and Puget Sound boundary conditions:

- Coastal ocean:
  - » Upwelling events off La Push occurred in roughly 10-day cycles, with low DO and high nitrate concentrations as shown by data from the buoy profiling the 20-90 m layer of the water column. Chlorophyll *a* levels increased following these events.
  - » More frequent "blooms", indicated by high values of chlorophyll *a*, were observed off La Push in 2012 than in 2011. Freshwater effects, likely from the Columbia River, were observed in the surface data record.
- Admiralty Inlet:
  - » Seasonal cycles in Admiralty Inlet bottom-mounted mooring data showed high variability in summer and more uniformity in winter. Upwelled Pacific Ocean water with low DO was observed in Admiralty Reach predominantly in the summer with occasional events in the winter.

River inputs:

- Through most of 2012, river flows in the Puget Sound region exceeded historical medians, except during the unusually warm, dry period extending from late August through mid-October when most rivers dropped below historical levels.

Water quality:

- Temperature and salinity:
  - » The entire water column showed colder and fresher conditions in 2012 relative to the 1999-2011 baseline, continuing anomalies from 2011.
  - » Compared to 2011, fewer but stronger episodes of warm/fresh surface water associated with the Fraser and Skagit River flows were observed at Triple Junction.
  - » A persistent freshwater lens inhibited mixing in Hood Canal, whereas stratification was less persistent in Carr Inlet and at Hansville just inside Admiralty Reach.
  - » Tribal canoe journey data revealed moderate to high marine surface water temperatures in July 2012 relative to past years despite the higher than normal river flows.
  - » Surface waters in the San Juan Channel and at a station in the Strait of Juan de Fuca were warmer early in the fall in response to persistent sunny and warm weather but switched to colder conditions by mid-October relative to a nine year baseline established in 2004. Surface waters in the Main Basin were also warmer than normal in late summer/early fall due to the unusual warm and dry weather.
- Nutrients and chlorophyll:
  - » Macro-nutrient (NO_3 and PO_4) concentrations increased and silica to nitrogen (Si:DIN) ratios decreased, continuing a 13-year trend. This nutrient ratio shift favors non-silicified phytoplankton, and large surface blooms of non-silicified species were frequently observed in many places throughout Puget Sound.
    - Despite large and frequent phytoplankton blooms, sub-surface (>1-50 m) phytoplankton biomass has declined over the past 13 years.
    - Daily surface transects by the Victoria Clipper indicate that the timing of the spring phytoplankton bloom was a few weeks earlier in 2012 than the previous year yet the overall timing of the spring bloom in early April was not unusual.
    - The 2012 spring bloom in the Main Basin was substantial and resulted in a measurable reduction in nitrate concentrations in surface waters until May.
    - An unusually large fall bloom occurred in September 2012, following a 2-month period of warm and dry weather, and was comprised of a variety of both diatoms and dinoflagellates. This resulted in a reduction in nitrate concentrations in September and a spike in ammonia levels in October following degradation of the bloom.
    - Profiling buoys captured an early surface spring bloom in southern Hood Canal in February and a very strong sub-surface bloom (10 m or below) in May. This spring bloom was much earlier than in Carr Inlet or the Main Basin.
    - Larger than average blooms were observed in the fall in the San Juan Channel and the Strait of Juan de Fuca relative to a nine year baseline established in 2004.
- Dissolved oxygen:
  - » The DO deficit of the water column was lower implying more oxygen availability relative to a baseline established in 1999. This continues an anomaly that started in 2011.

- » DO concentrations in Quartermaster Harbor dropped below 1.0 mg/L in September, the lowest levels recorded since 2008.
- » DO levels increased in the upper 30 m of the water column in Main Basin due to intense primary productivity associated with the large April and September phytoplankton blooms.
- » DO levels in Hood Canal were higher than previous years and hypoxic conditions were not observed at any of the profiling buoy locations – with the exception of a short and less intense event at the Twanoh buoy in southern Hood Canal, the shortest event for the entire seven year record.
- » No cases of fish kills were reported in Hood Canal during 2012.

Plankton:

- Phytoplankton:
  - » The chain-forming diatoms *Chaetoceros, Thalassiosira, Detonula, Skeletonema* and *Pseudo-nitzschia*, along with the dinoflagellates *Ceratium* and *Akashiwo*, were the most abundant genera in the Main Basin.
  - » The spring bloom was followed by an unusually sharp drop in the diatom component of the phytoplankton community in summer.
  - » *Noctiluca scintillans*, a heterotrophic dinoflagellate, may be an effective grazer in Puget Sound, capable of clearing phytoplankton biomass from surface waters within a few days in the Main Basin. These “clearing events” were less extensive in 2012 than in 2011.
- Harmful algae:
  - » *Alexandrium* spp. were absent or detected at low abundances from most sampling locations, with the exception of Discovery Bay, Sequim Bay, and Quartermaster Harbor – shellfish growing area closures due to toxins produced by *Alexandrium* spp. occurred in Discovery and Sequim Bays.
  - » The 2012 spatial distribution of *Alexandrium catenella* resting cysts that overwinter in the surface sediments of Puget Sound was similar to 2011, but abundances were lower at most locations.
  - » *Pseudo-nitzschia* spp. was common throughout Puget Sound, with the highest cell counts observed in Sequim Bay, Quartermaster Harbor, and Penn Cove; however, no shellfish closures occurred due to domoic acid levels.
  - » *Dinophysis* spp. was identified at all sampling sites, with cells appearing in mid-April and maintaining a sustained presence until early December. Highest cell abundances were detected in Quartermaster Harbor and Sequim Bay.
  - » *Heterosigma* sp. had variable presence among the various monitoring sites.

- Biotoxins:
  - » Paralytic Shellfish Poisoning (PSP) toxins were much higher compared to 2011. Highest values were detected in mussels near Kingston at over 125 times the FDA standard.
  - » Twenty eight commercial growing areas and 31 recreational harvest areas were closed due to PSP toxins.
  - » Nine PSP illnesses were reported from people eating mussels from areas that were closed to recreational harvest.

  - » There were no commercial or recreational harvest closures for domoic acid and no Amnesiac Shellfish Poisoning illnesses were reported.
  - » One commercial growing area and 13 recreational areas were closed due to Diarrheic Shellfish Poisoning (DSP) toxins but there were no DSP illnesses reported.
  - » The DSP closure in Hood Canal was the first biotoxin closure of any kind in this area.

Bacteria and pathogens:

- Fecal indicator bacteria:
  - » All offshore monitoring sites in the Main Basin passed the Washington State geometric mean and peak standards for fecal coliforms during 2012.
  - » Eight of 20 monitoring sites at marine beaches in the Main Basin within King County failed both the geometric mean and peak fecal coliform standards.
  - » The percentage of marine swimming beaches meeting the EPA enterococcus bacteria standard increased from 81% for 2011 to 88% for 2012.
- *Vibrio parahaemolyticus:*
  - » There were 74 confirmed illnesses due to the consumption of shellfish contaminated with *Vibrio parahaemolyticus.* Of these illnesses, 66 were linked to commercial shellfish harvest and 8 to recreational shellfish harvest.

Marine birds:

- Pigeon guillemot:
  - » 149 burrows were counted during the first comprehensive survey of pigeon guillemot burrows on Protection Island.
  - » Preliminary results suggest a lower breeding success (25-31%) compared to 2011 (38-45%).
- Rhinoceros auklet:
  - » Overall, the Salish Sea rhinoceros auklet population size has likely increased, and diet quality and reproduction have remained remarkably stable, relative to the 1970’s.

Large-scale climate and wind patterns in the Pacific Northwest

ENSO, PDO, and NPGO are large-scale climate variations that have similarities and differences in the ways that they influence the Pacific Northwest. ENSO and PDO are patterns in Pacific Ocean sea surface temperatures that can also strongly influence atmospheric conditions, particularly in winter. For example, warm phases of ENSO and PDO generally produce warmer than usual coastal ocean temperatures and drier than usual winters. The opposite is generally true for cool phases of ENSO and PDO. ENSO climate cycles usually persist 6 to 18 months, whereas phases of the PDO typically persist for 20 to 30 years. In Puget Sound, warm water temperature anomalies are produced during the winter of warm phases of ENSO and PDO and can typically linger for 2 to 3 seasons. For PDO, these anomalously warm waters can reemerge 4 to 5 seasons later (Moore et al. 2008). In contrast, the NPGO, which is related to processes controlling sea surface height, has a stronger effect on salinity and nutrients, as opposed to temperature. Wind is an important factor in the NPGO, which can influence the seasonal wind pattern in the eastern Pacific Ocean. On the outer Washington coast, seasonal winds shift from dominantly southerlies during winter to northerlies during summer and drive some of the largest variation in offshore coastal conditions: upwelling vs. downwelling. Upwelling brings deep, cold, salty, nutrient-rich, oxygen-poor waters to the surface and into the Strait of Juan de Fuca as source water for Puget Sound.

Large-scale climate variability and wind patterns

Large-scale patterns of climate variability, such as El Niño-Southern Oscillation (ENSO) the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO), can strongly influence Puget Sound's marine waters. In addition, seasonal upwelling winds on the outer coast, with intrusion of upwelled waters into Puget Sound, are a strong signal that has similar indicators as human-sourced eutrophication (i.e., high nutrients, low oxygen). ***It is important to document and understand these regional processes and patterns so that water quality data may be interpreted with these variations in mind.***

A. El Niño-Southern Oscillation (ENSO):

Source: Rosa Runcie (Rosa.Runcie@noaa.gov) (NOAA, SWFSC); http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html; http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory/

The Multivariate ENSO Index (MEI) reflects the behavior of ENSO using six main observed variables in the tropical Pacific. Positive values of the MEI indicate warm phases (El Niño) and negative values indicate cool phases of ENSO (La Niña). The MEI turned strongly negative in April 2010, reaching large negative values not seen since 1955 and the mid-1970s (Figure 1A). In 2012, a mature La Niña continued in January with below-average sea surface temperatures (SST) persisting across the equatorial Pacific Ocean. In February and March 2012, La Niña conditions weakened with near-to-above average SSTs in the eastern equatorial Pacific Ocean (Figure 1B). ENSO-neutral conditions prevailed in May 2012, following the dissipation of La Niña in April with below-average SSTs weakening across most of the equatorial Pacific Ocean and above-average SSTs persisting in the east. During June 2012, ENSO-neutral conditions continued as reflected in both the oceanic and atmospheric anomalies and continued into July and August despite above-average sea surface temperatures across the eastern Pacific Ocean. From September to December 2012, the Pacific Ocean exhibited borderline ENSO-neutral/weak El Niño conditions. During December, equatorial SST anomalies were positive in the western Pacific Ocean, near zero in the central Pacific Ocean, and slightly negative in much of the eastern Pacific Ocean.

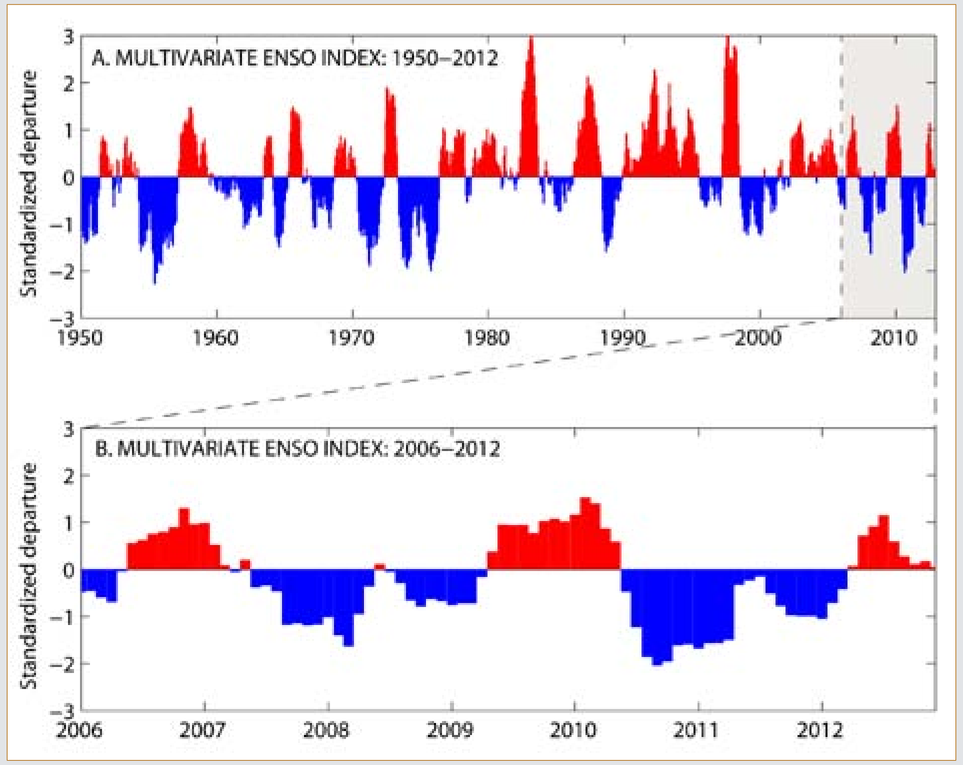


Figure 1. NOAA Physical Sciences Division monitors ENSO by basing the Multivariate ENSO Index (MEI) on the six main observed variables over the Pacific. These six variables are: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. Monthly values of the MEI are shown from A. 1950-2012 and B. 2006-2012. (http://www.esrl.noaa.gov/psd/enso/mei/table.html).

B. Pacific Decadal Oscillation (PDO)

Source: Bill Peterson (Bill.Peterson@noaa.gov) (NOAA, NWFSC); Skip Albertson (skip.albertson@ecy.wa.gov), Julia Bos, Christopher Krembs (Ecology); http://jisao.washington.edu/pdo/PDO.latest

The Pacific Decadal Oscillation (PDO) has been negative and cold ocean conditions in the Pacific Northwest have prevailed for most months since September 2007 (Figure 2). This run of negative values was interrupted by a brief and moderate El Niño event from August 2009 to May 2010 that temporarily warmed ocean temperatures, but otherwise the PDO has been strongly negative over a period of more than five years. The PDO was strongly negative throughout most of 2012, reaching a maximum value of -2.21 in September and then weakening into December 2012. Summer values, cumulated over May to September, were the fourth most negative since 1960 (-6.43 compared to -7.63 in 2008, -6.43 in 2011, and -6.36 in 1962).

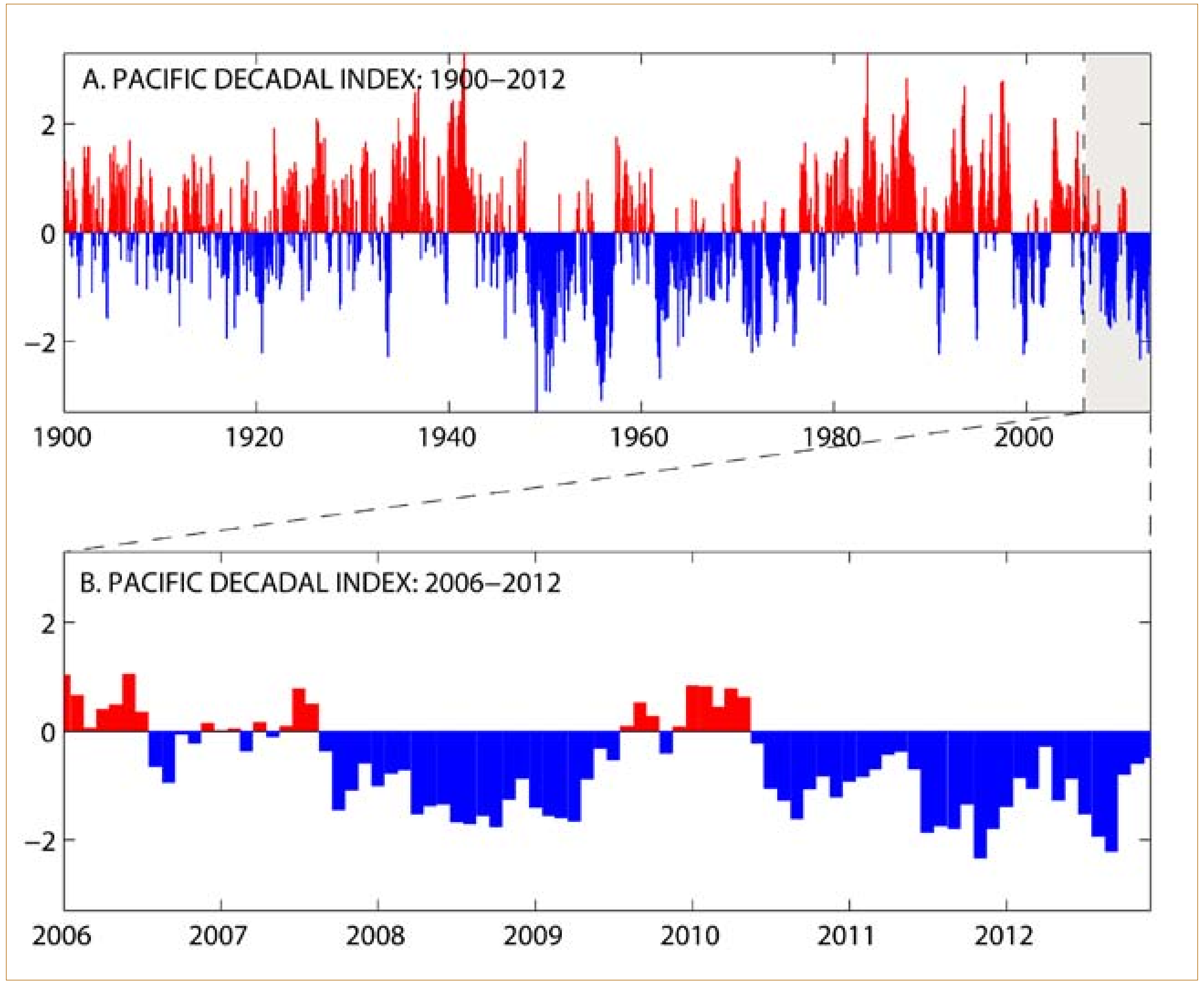


Figure 2. Monthly values of the Pacific Decadal Oscillation index (PDO) from A. 1900-2012 and B. 2006-2012.

The North Pacific Gyre Oscillation (NPGO) is a climate pattern of sea surface height variability in the Northeast Pacific. Fluctuations in the NPGO are driven by regional and basin-scale variations in wind-driven upwelling - the fundamental process controlling salinity and nutrient concentrations at the coast. The NPGO provides a strong indicator of fluctuations in the mechanisms driving planktonic ecosystem dynamics (Di Lorenzo et al. 2008).

C. North Pacific Gyre Oscillation (NPGO)

Source: Christopher Krembs (ckre461@ecy.wa.gov) (Ecology); http://www.o3d.org/npgo/

The NPGO has been showing positive values since the late 90's with the exception of intermittent negative values occurring between 2005 and 2007 (Figure 3). Since April 2007, NPGO values have been consistently positive and values in 2012 were very high (no current updates were available at the time of publication of this report past September 2012). High NPGO values suggest an elevated primary productivity pattern along Washington's coastline and the California Current that can extend into reaches of the Salish Sea and Puget Sound.

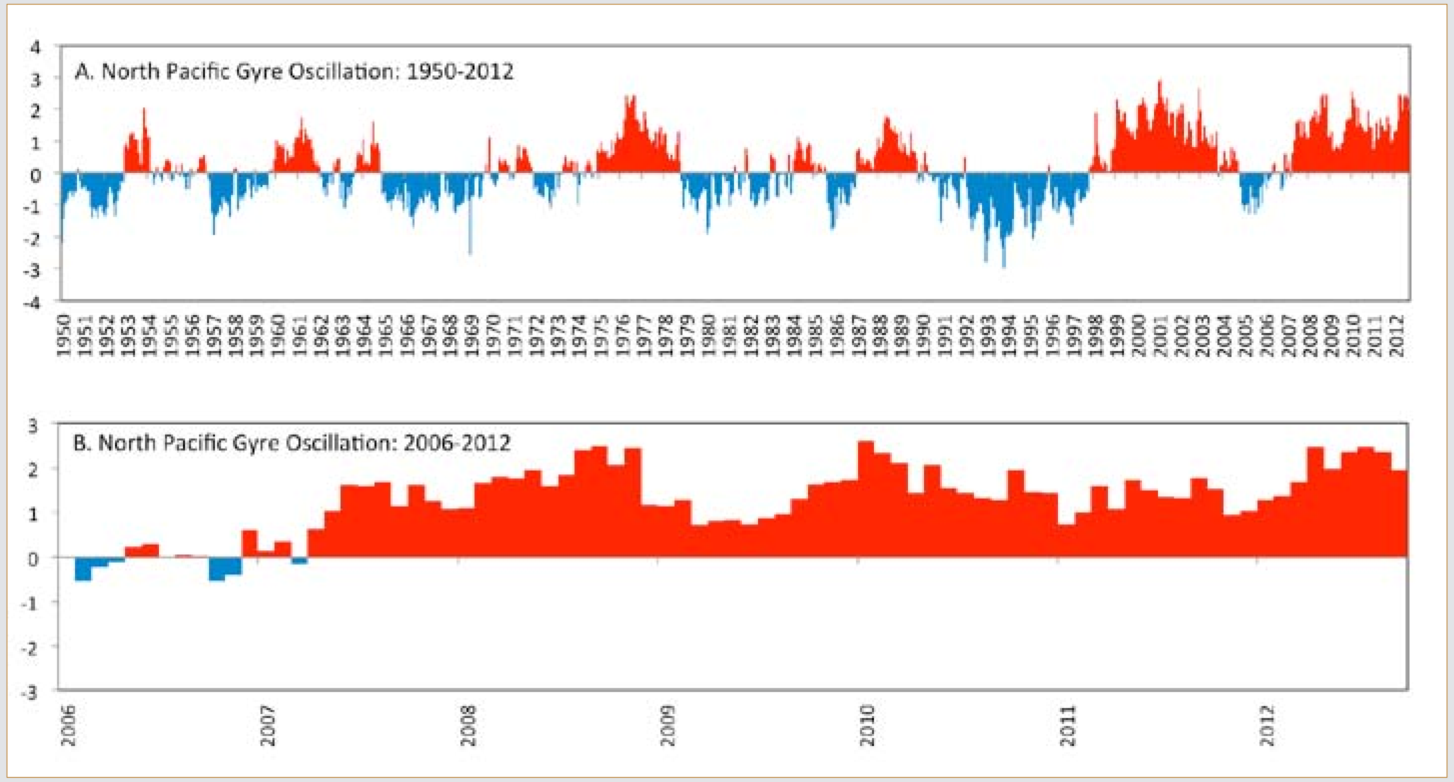


Figure 3. Monthly values of the North Pacific Gyre Oscillation index (NPGO) from A. 1950-2012 and B. 2006-2012.

Upwelling favorable winds (i.e., equatorward winds) on the outer Washington coast bring deep ocean water in through the Strait of Juan de Fuca and into Puget Sound. The upwelled water is relatively cold and salty, with low oxygen and high nutrient concentrations. The typical upwelling season for the Pacific Northwest is from April through September.

D. Upwelling index

Source: Skip Albertson (skip.albertson@ecy.wa.gov) Julia Bos, Christopher Krembs (Ecology), www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

Monthly summary statistics of the upwelling index at 48°N and 125°W are plotted in statistical historical context. In 2012, upwelling index anomalies were generally within expected historic ranges with the exception of March and April when stronger than normal downwelling occurred. Likewise, upwelling was weaker in June (Figure 4).

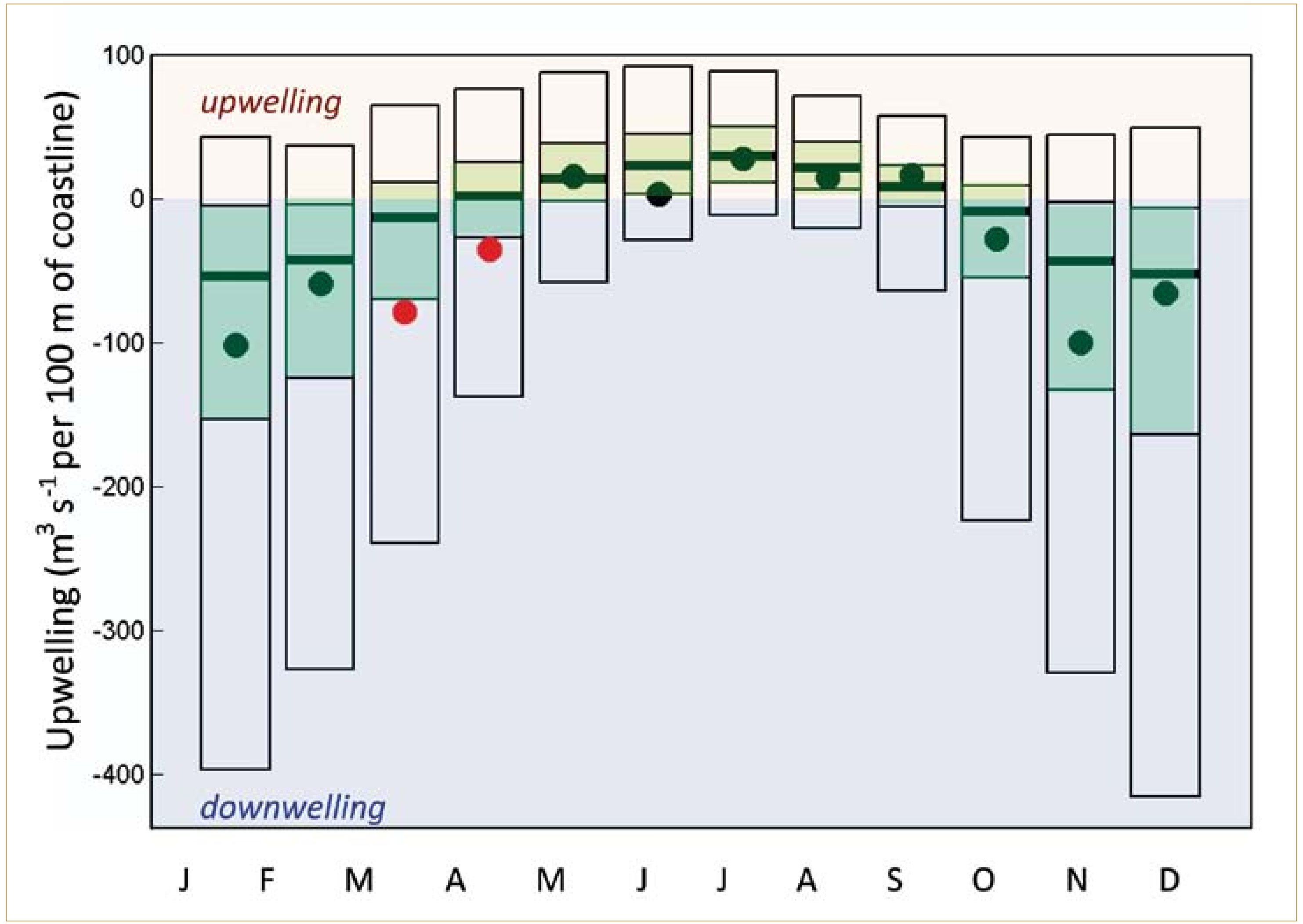


Figure 4. Monthly averages of the coastal upwelling index (PFEL, NOAA) at 48°N and 125°W for 2012 (red and black circles). Values in the red and blue shaded areas indicate upwelling and downwelling conditions, respectively. Historic monthly values from 1967-2012 are used to calculate the median (i.e., 50th percentile) which is represented by the solid black lines, and the interquartile ranges are represented by the green box. If an observed value for a particular month occurs outside of the interquartile range (implying that values outside this range occur less than 50% of the time for that particular month), Ecology considers the value to be significantly different. The larger box surrounding the interquartile range represents the 5th and 95th percentiles.

Local climate and weather

Local climate and weather conditions can also exert a strong influence on Puget Sound marine water conditions on top of the influences of longer-term large-scale climate patterns. Variations in local air temperature best explain variations in Sound-wide water temperatures (Moore et al. 2008).

A. Regional air temperature and precipitation

Source: Jim Johnstone (jajstone@u.washington.edu) (UW, JISAO); http://jisao.washington.edu/

During the 2012 calendar year, Puget Sound experienced cool and wet conditions in comparison to the 1981-2010 climatology (Figure 5). Puget Sound air temperatures, based on six long-term stations, fell 0.5°C below the annual average, while precipitation totals were 21% above normal. Temperatures in 2012 continued a string of unusually cool years that began in 2007.

In early 2012, the transition from winter to summer was unusually late; 5 of the 6 months from February through July were cooler and wetter than normal, replaying similar conditions during early 2011. The prolonged winter storm season led to a Cascade snow pack in May and June that was approximately double the average depth, based on snow water measurements at Stevens Pass.

The late summer months of August and September saw a shift to unusually warm and dry conditions. Puget Sound precipitation was almost entirely absent, and temperature anomalies rose to 0.8°C above normal. In the Seattle area, early October (through the 11th) also had no measureable precipitation and was the driest 11-day period for this time period in over 20 years. This two and a half month stretch between August and early October was the driest period recorded in Seattle history. The intense summer ended abruptly in mid-October with rainfall totals that more than doubled the norm, and two of the final three months of the year were unusually wet.

The Puget Sound climate of 2012 can be summarized as a year of seasonal extremes and contrasts. The spring and fall were abnormally long and winter-like, while the summer was brief but intense.

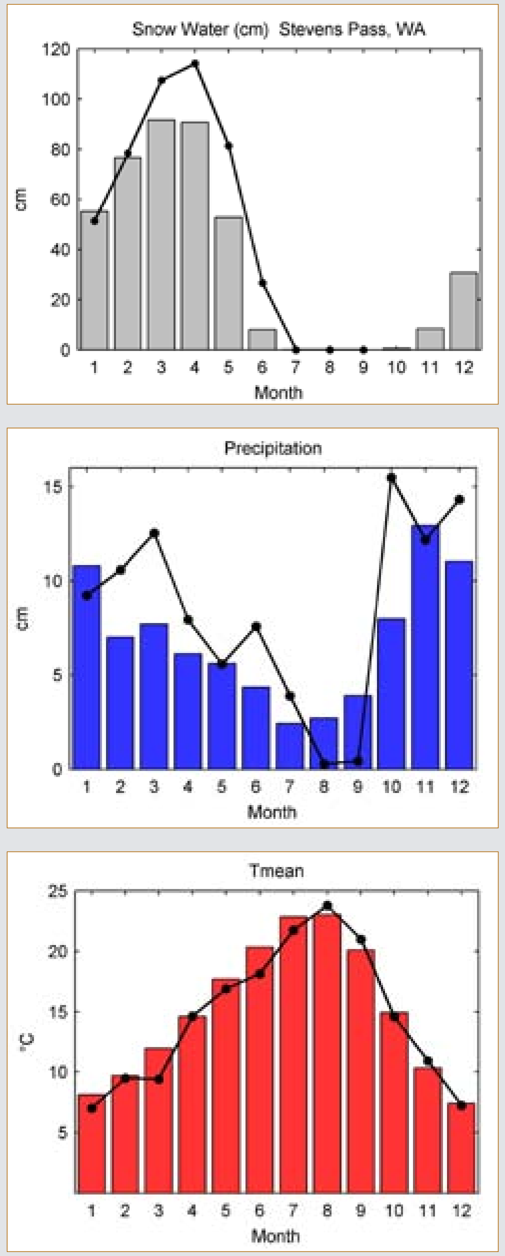


Figure 5. Monthly climatology and 2012 conditions in the Puget Sound region. Bars show the 1981-2010 climatological means; dotted lines indicate 2012 values. Top panel: Snow water equivalent, Stevens Pass, WA SNOTEL site. Middle panel: Monthly precipitation averaged over six long-term Puget Sound stations from the US Historical Climate Network (Bellingham, Blaine, Everett, Olga, Port Townsend and Seattle). Bottom panel: Monthly mean temperature averages from the same six long-term Puget Sound stations.

B. Local air temperature and solar radiation:

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Julia Bos, Christopher Krembs (Ecology);
www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html; National Weather Service (NWS), http://w1.weather.gov/xml/current_obs/KPAE.xml (Everett), http://w1.weather.gov/xml/current_obs/KOLM.xml (Olympia)

In 2012, air temperatures were lower than the historical average (1971-2000; National Climatic Data Center) at both the north (Everett) and south (Olympia) Puget Sound basin monitoring sites. Patterns were most pronounced in the north and during the first half of the year (Figure 6). A few extended episodes of warmer temperatures occurred in the fall at both sites. Sunlight was ubiquitously lower from January through July. Sunnier conditions occurred from August through early October followed by a cloudier than normal condition for the rest of 2012.

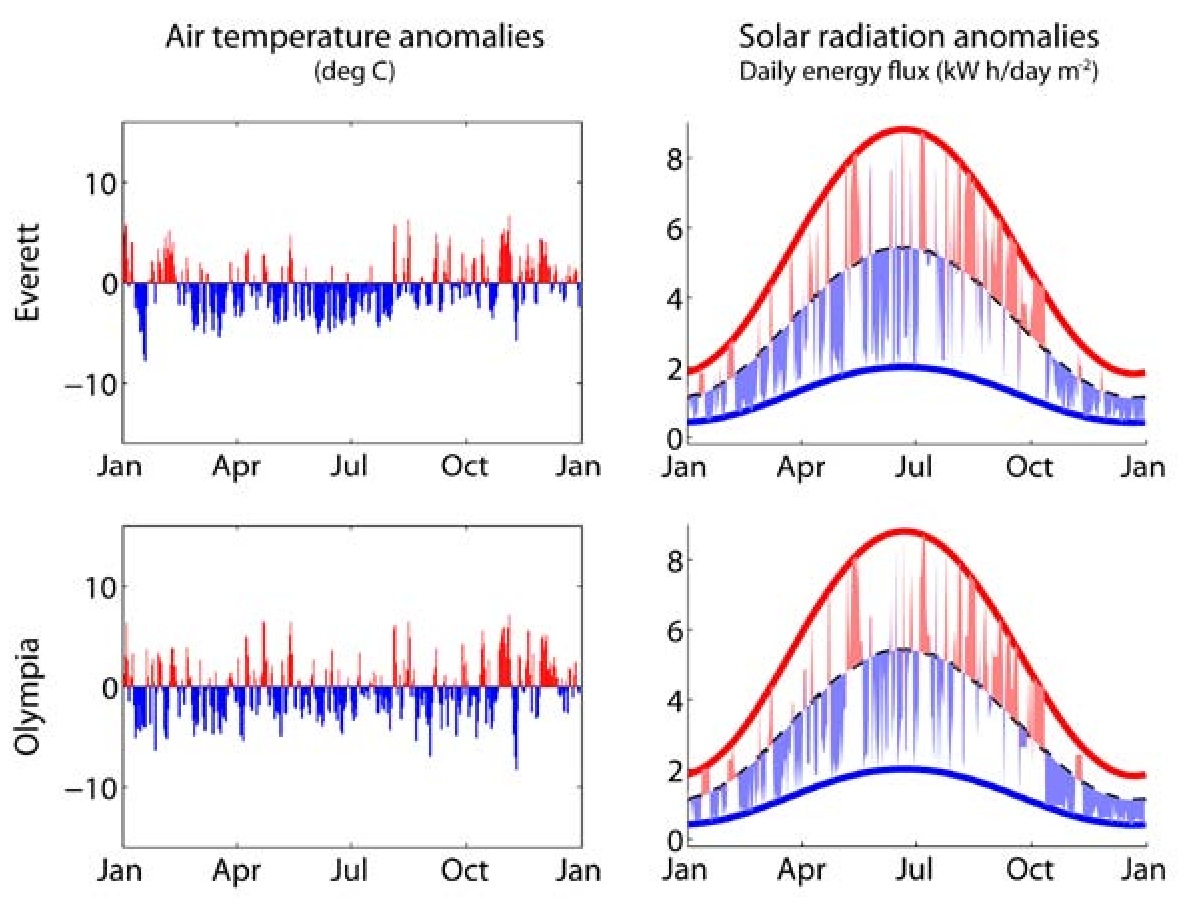


Figure 6. Air temperature (left panel) and solar radiation (right panel) anomalies at Everett and Olympia for 2012. Red indicates higher than average, blue indicates lower than average.

Coastal ocean and Puget Sound boundary conditions

The waters of Puget Sound are a mix of coastal ocean water and river inputs. Monitoring the physical and biochemical processes occurring at the coastal ocean provides insight into this important driver of marine water conditions in Puget Sound.

A. Coastal ocean

Source: Matthew Alford, Jan Newton (newton@apl.washington.edu), John Mickett (UW, APL), and Al Devol (UW); http://www.nanoos.org, http://wavechasers.uw.edu

Two buoys maintained by the Northwest Association of Networked Ocean Observing Systems (NANOOS) in the coastal ocean off La Push on the outer Washington coast yield insight into water properties and dynamics of this coastal boundary condition for Puget Sound. Data from the Northwest Enhanced Moored Observatory (NEMO) subsurface profiling buoy located off the coast of Washington near La Push revealed seasonal and event-driven dynamics from May through August of 2012 (Figure 7). Data are collected from the 20-90 m layer of the water column (total water depth is ~100 m). The surface layer below 20 m gets progressively cooler and saltier from May through August, consistent with annual upwelling that intensifies over the summer (see Figure 4). Oxygen and nitrate variability are dominated by events occurring roughly 10 days apart when the entire water column shows low oxygen and high nitrate concentrations. Upwelling may be involved in these events, indicated by the halocline getting shallower. However, at the same time, temperature and salinity gradients do not change as much as the gradients in oxygen and nitrate, indicating other processes may also be influencing these dynamics. One explanation for the differences between signals in the physical and biochemical properties is that waters upwelling offshore move onshore, and due to shear from the bottom this produces different arrival times for some of these features. Regardless of mechanisms, NEMO data show that the coastal ocean is highly dynamic over short time scales.

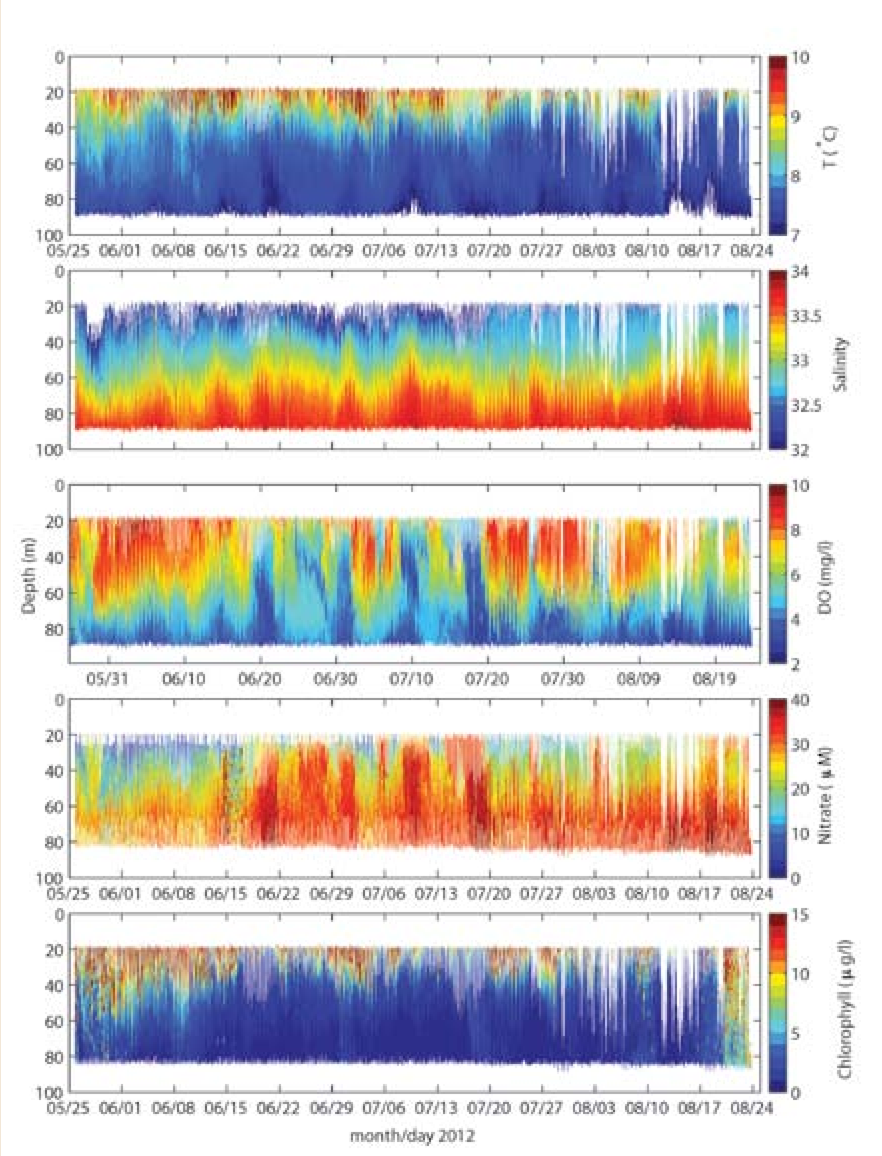


Figure 7. Data from NEMO sub-surface profiling buoy, located in offshore coastal Washington waters near La Push. Profiles of temperature, salinity, DO, nitrate and chlorophyll a were collected from the 20-90 m layer of the water column, at a site where the depth is 100 m, from May through August, 2012.

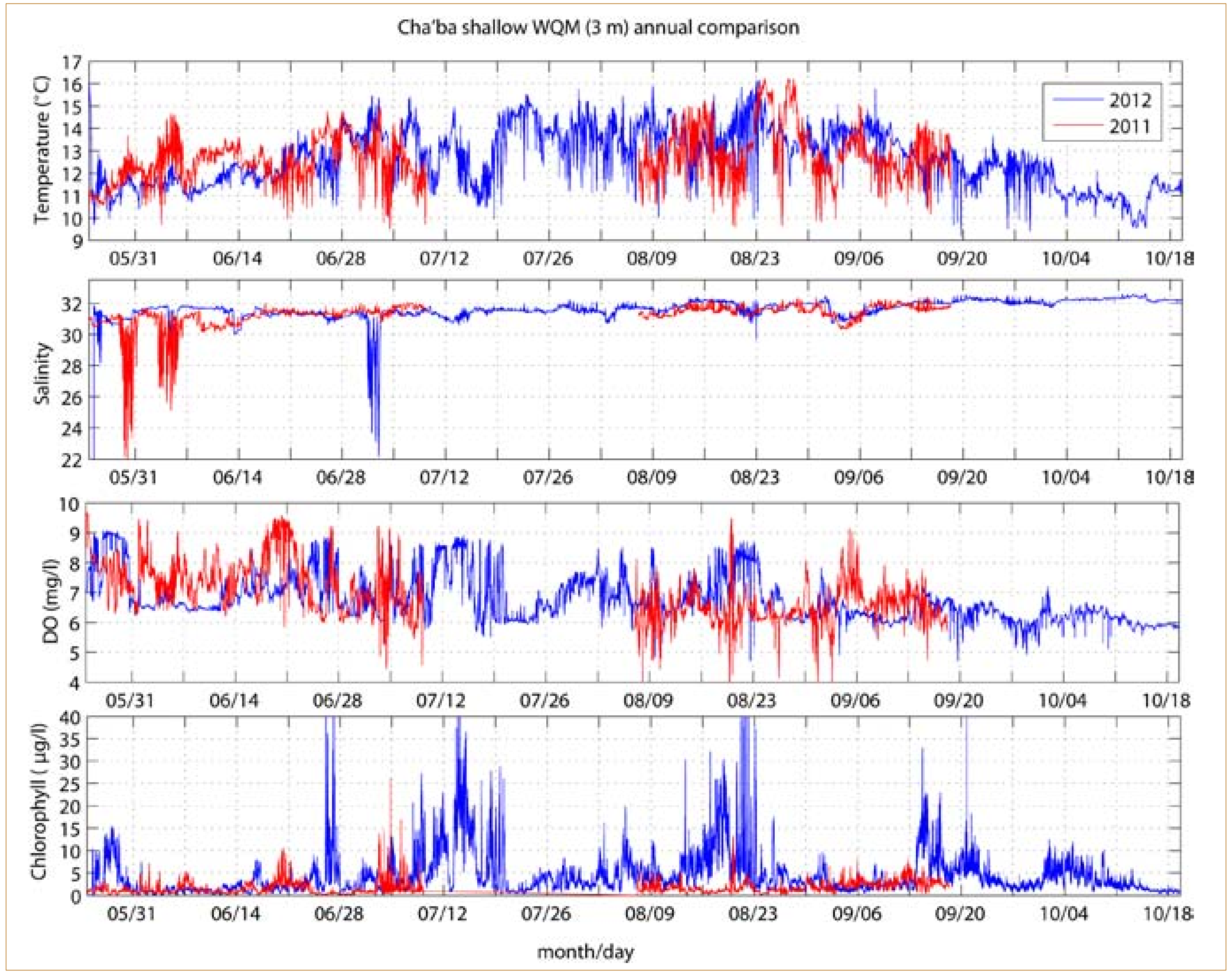


Figure 8. Data from the Cha'ba surface buoy, located in offshore coastal Washington waters near La Push at 3 m depth. Time series data of temperature, salinity, DO, and chlorophyll *a* were collected during the summer from May through August, for 2011 and 2012.

The Cha'ba surface buoy is located approximately 0.5 miles from the NEMO profiler and measures water properties at 3 m depth. Data for both 2011 and 2012 reveal short-term variations in water properties (Figure 8), but with the same range in variation both years for most variables. Notable low salinity events were observed during both years and are associated with freshwater influences, likely from the Columbia River based on northward flowing currents measured at the mooring at these times. The exception is chlorophyll *a* data, which indicate large sustained bloom events during 2012 that were not evident during 2011, although there are data gaps in the 2011 record. Major blooms during July and August 2012 corresponded with high oxygen concentrations. These events were regularly associated with either sustained (week of July 13th, 2012) or rapid (August 22nd 2012) drops in temperature. The largest blooms occur at depths above 20 m, revealed by the comparison of the chlorophyll data at 3 m with that from 20-90 m layer. However, measurable chlorophyll *a* levels are observed between 20 and 60 m depth, meaning chlorophyll *a* is either accumulating (phytoplankton cells sinking) or is mixed downwards from the surface.

Coastal ocean and Puget Sound boundary conditions (cont.)

Admiralty Inlet connects the Strait of Juan de Fuca to Puget Sound. Conditions at depth at Admiralty Inlet are representative of the water masses coming into the Sound from the coastal ocean. These conditions are responsive to the tides and upwelling (i.e., northerly) winds on the outer Washington coast.

B. Admiralty Inlet

Source: Christopher Krembs (christopher.krembs@ecy.wa.gov), David Mora, Suzan Pool, and Julia Bos (Ecology), and Jim Thomson (APL); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html, http://depts.washington.edu/uwefm/people/Thomson.shtml

In collaboration with UW APL, Ecology deployed a sensor package on a mooring at the bottom of Admiralty Inlet to monitor the ocean water exchange across the sill between the Strait of Juan de Fuca and Puget Sound. The continuous data provides a temporal context for describing the seasonal and event driven dynamics of the connectivity of Pacific Ocean and Puget Sound waters. A strong seasonality characterizes all three variables; temperature, salinity and oxygen. While temperature and salinity show maxima and minima in late summer and winter, lagging each other by about a month, the seasonal cycle of oxygen is shifted. Oxygen maxima in spring and minima in fall reflect the seasonal cycle in phytoplankton productivity and upwelling patterns off the coast of Washington. The largest tidally induced variability in temperature, salinity and oxygen appears during the summer/fall period (Figure 9) and corresponds to periods of upwelling along the outer Washington coast (see Figure 4). Strong gradients in temperature, salinity and oxygen occur as water moves across the Admiralty sill during each tidal cycle. These gradients are small in winter but may occasionally be responsible for distinct events of low oxygen water entering Puget Sound. Winter variations in temperature and oxygen are correlated with warmer, saltier, low-oxygen water and coincide with persistent southerly winds (data not shown). Damage to mooring sensors from drifting debris created significant data gaps for 2012.

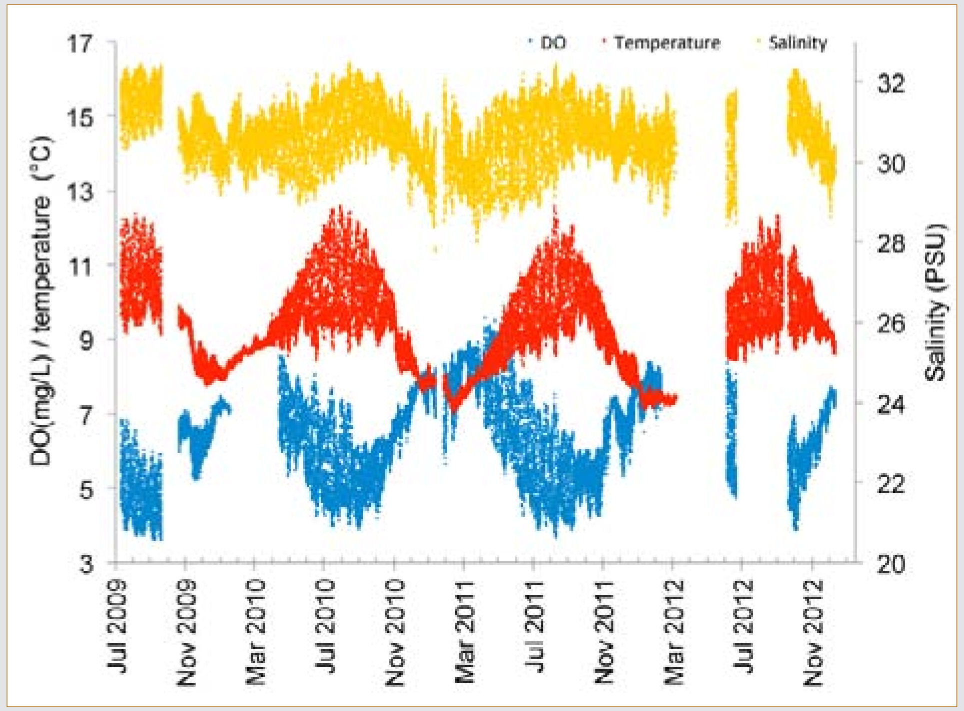


Figure 9. Admiralty Inlet mooring data from2009-2012 showing seasonality and variability in temperature (red), dissolved oxygen concentration (blue), and salinity (gold), collected at 30 minute intervals from a depth of 65 m.

Ocean and climate affect Puget Sound water quality

Authors: Christopher Krembs, Skip Albertson, Julia Bos, Mya Keyzers,
Laura Friedenberg, Carol Maloy (Ecology)

The Department of Ecology uses monthly data from their network of long-term stations, along with related climate information from sources such as NOAA, to better understand how ocean boundary conditions and climate variability affect Puget Sound water quality parameters. Teasing apart the influences of natural drivers of variability, such as climate oscillations, from human impacts is critical for evaluating the effectiveness of management actions. The Pacific Decadal Oscillation (PDO) is a climate pattern that is characterized by sea surface temperature anomalies in the North Pacific Ocean. The PDO indicated a cool phase from 1999-2002, a warm phase from 2003-2006, and cool phases again in 2008 and 2011-2012 (Figure 10A). The thermal energy content in Puget Sound waters 0-50 m deep significantly correlates positively with the PDO (Spearman Rank Correl. $p<0.05$, $n=14$). The NOAA (PFEL) anomalies of the Upwelling Index is based on the north-south component of offshore winds. Upwelling along the Washington Coast brings saltier water onto the shelf, which enters Puget Sound and influences the salinity. The salt content of Puget Sound waters 0-50 m deep positively correlates with upwelling index anomalies (Spearman Rank Correl. $p<0.05$, $n=13$), with higher salinity occurring during stronger upwelling years (Figure 10B). The integrated dissolved oxygen (DO) deficit for Puget Sound waters deeper than 20 m also positively correlates with the upwelling index (Spearman Rank Correl. $p<0.05$, $n=11$), showing that upwelled Pacific Ocean water drives the Puget Sound-wide annual average oxygen in the deep waters and highlights the importance of oceanic boundary conditions regulating the Puget Sound oxygen budget (Figure 10C). (For an explanation of the DO-deficit, see the section on Puget Sound long-term stations in this report.) The North Pacific Gyre Oscillation (NPGO) is a climate pattern that tracks changes in the North Pacific gyre circulation and explains key physical-biological ocean variables in the California Current system. DO anomalies in Puget Sound waters 0-50 m deep positively correlate with the NPGO (Spearman Rank Correl. $p<0.05$, $n=14$), confirming that productivity in the upper water layer of Puget Sound follows larger productivity patterns along the Pacific coast (Figure 10D).

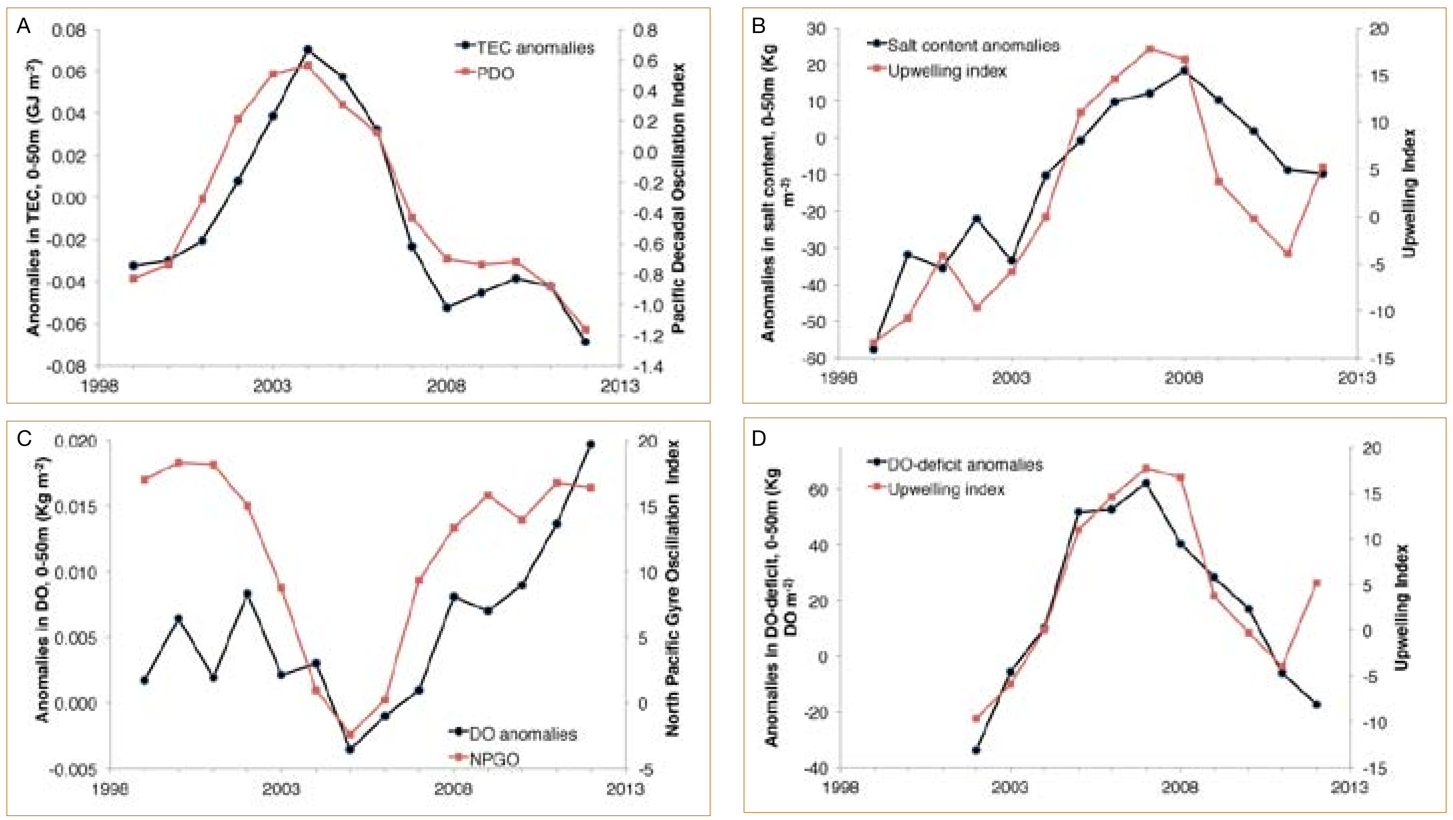


Figure 10. A. The Pacific Decadal Oscillation (PDO) index and thermal energy content (TEC) anomalies in Puget Sound; The upwelling index at 48°N and 125°W from NOAA PFEL and B. salt content anomalies in Puget Sound, and C. dissolved oxygen deficit anomalies in Puget Sound; and D. The North Pacific Gyre Oscillation (NPGO) index and dissolved oxygen content anomalies in Puget Sound. Results are presented as annual averages of monthly anomalies relative to the baseline established from 1999-2008.

The waters of Puget Sound are a mix of coastal ocean water and river inputs. The flow of rivers that discharge into Puget Sound is strongly influenced by rainfall patterns and the elevation of mountains feeding the rivers. Freshwater inflows from high elevation rivers peak twice annually from periods of high precipitation in winter and snowmelt in spring and summer. Low elevation watersheds collect most of their runoff as rain rather than mountain snowpack and freshwater flows peak only once annually in winter due to periods of high precipitation. The salinity and density-driven circulation of Puget Sound marine waters are influenced by river inflows.

A. Puget Sound rivers

Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PS Partnership) and U.S. Geological Survey; http://waterdata.usgs.gov/nwis/uv/?referred_module=sw

In Puget Sound, most rivers showed generally higher than average flows early in the year with especially high flows through early summer (consistent with the unusually rainy weather; Figure 11). Flows mostly dropped below historic means (see panels in Figure 11 for baseline time periods at each station) in late summer and well into October. These low flows followed a period of exceptionally sunny, dry weather from August to early October. Flows rose above historical medians again in November through early December. A short dry period in late December resulted in many rivers again dropping below historic means at the very end of the calendar year.

In slight contrast to this pattern, the Nisqually River showed higher than average flows throughout the year with a less pronounced late summer drop. Similarly in Hood Canal, the Skokomish River maintained above average flows throughout the entire the year.

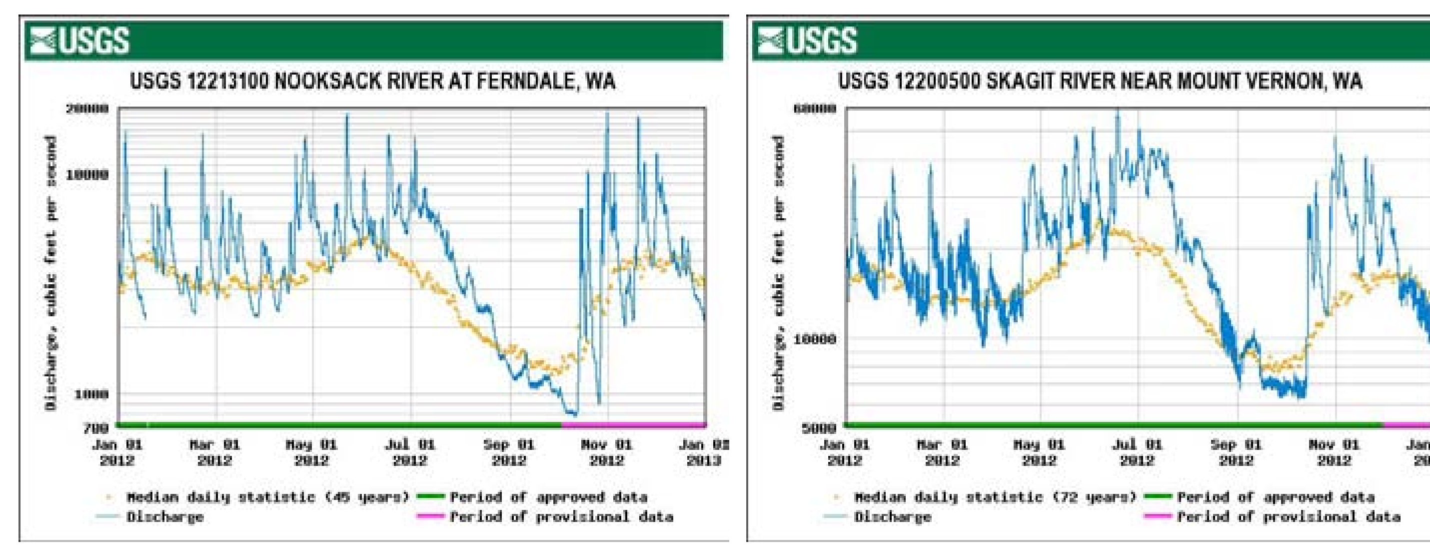
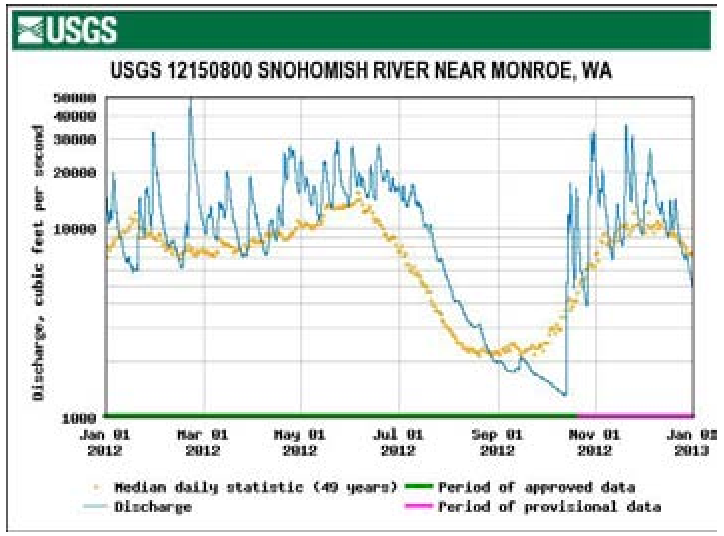
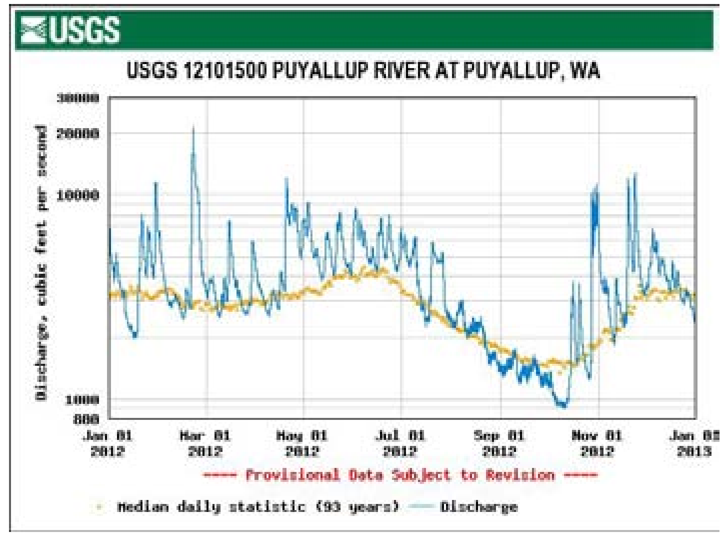
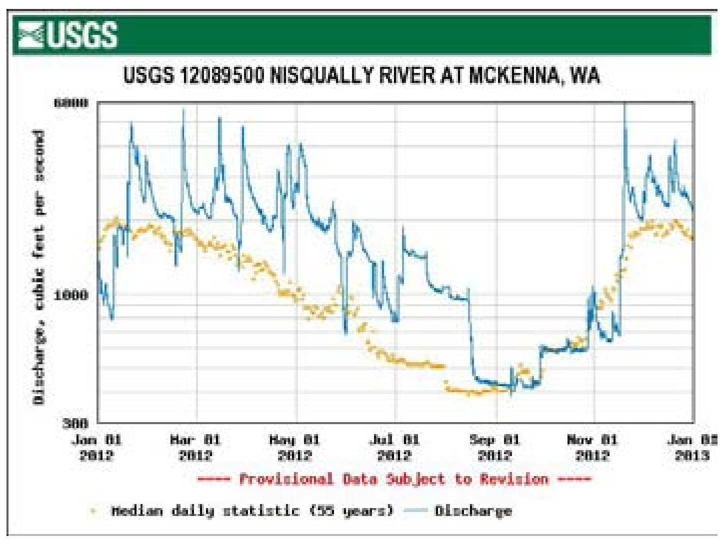
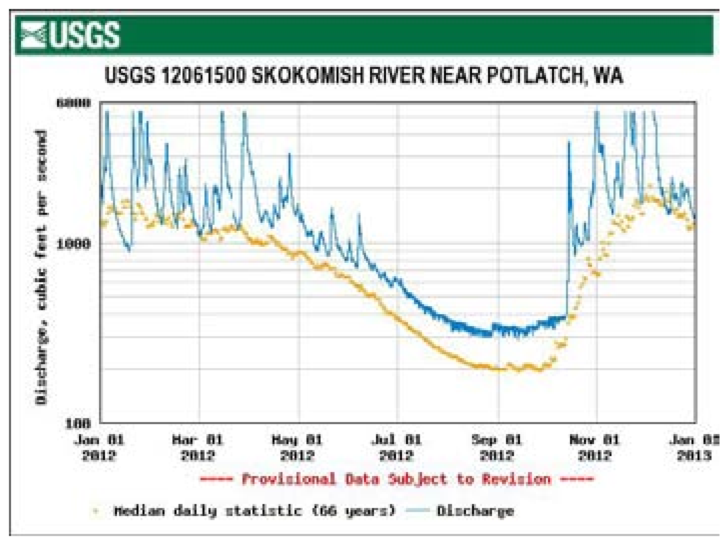


Figure 11. Daily river discharge at sites in the Nooksack, Skagit, Snohomish, Puyallup, Nisqually, and Skokomish Rivers for 2012. Median values from historic records are also shown.









B. Fraser River:

Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PS Partnership) and Environment Canada; http://www.wateroffice.ec.gc.ca/index_e.html

Fraser River flows were similar to long-term averages from January to April 2012 (Figure 12). From May to August, snowmelt from a larger than usual snowpack resulted in much higher than average flows. Following a prolonged dry spell in late summer, flows dropped to considerably below average in September and October, returning to normal again in November and December.

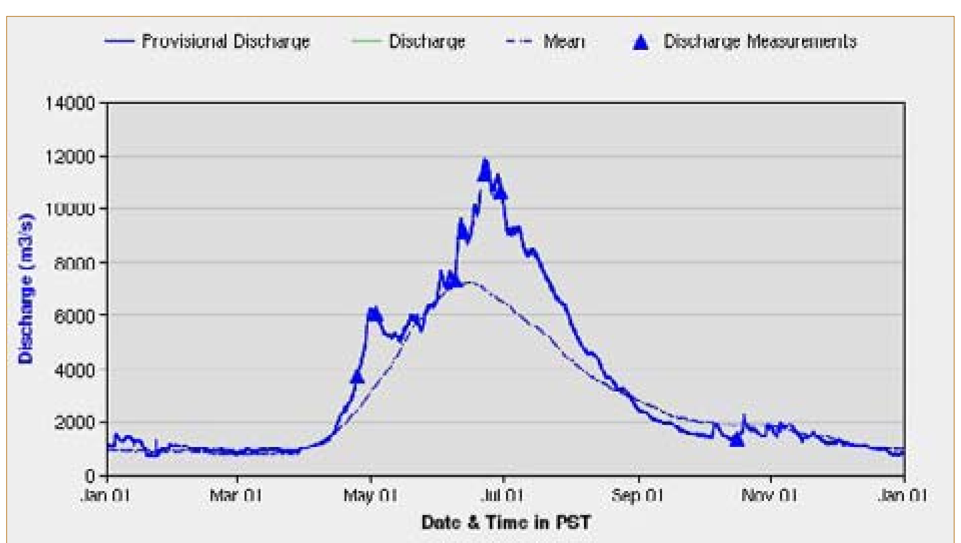


Figure 12. Daily Fraser River discharge at Hope for 2012. The mean values from historic records are also shown. (Note: 1 m³/s = 35.3 cfs)

Water quality

Temperature and salinity are fundamental water quality measurements. They define seawater density and as such are important for understanding estuarine circulation. Various organisms also may have tolerances and preferences for thermal and saline conditions. Nutrients and chlorophyll give insight into the production at the base of the food web. Phytoplankton are assessed by monitoring chlorophyll, their photosynthetic pigment. In Puget Sound, like most marine systems, nitrogen nutrients sometimes limit phytoplankton growth. On a mass balance, the major source of nutrients is from the ocean; however, rivers and human sources also contribute to nutrients loads. Dissolved oxygen in Puget Sound is quite variable spatially and temporally and can quickly shift in response to wind, weather patterns and upwelling. In some parts of Puget Sound, dissolved oxygen is measured intensively to understand the connectivity between hypoxia and large fish kills.

A. Puget Sound long-term stations

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Skip Albertson, Brandon Sackmann, David Mora, Mya Keyzers, Laura Friedenberg, Suzan Pool, Carol Maloy (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

The Washington Department of Ecology's long-term stations in Puget Sound provide the temporal coverage and precision needed to identify long-term trends.

i. Salinity and Temperature

Monitoring at the Washington Department of Ecology's long-term station network shows that salinity conditions in 2012 were fresher relative to the historical baseline of 1999-2008 data (Figure 13). In mid-January, Puget Sound responded to a freezing snap with a short-term relaxation of the salinity anomaly as water was retained on land as snow and ice. Overall in 2012, Puget Sound water temperatures were colder than the historical baseline from 1999-2008 (not shown). The colder, fresher conditions continued a pattern that had started in 2011.

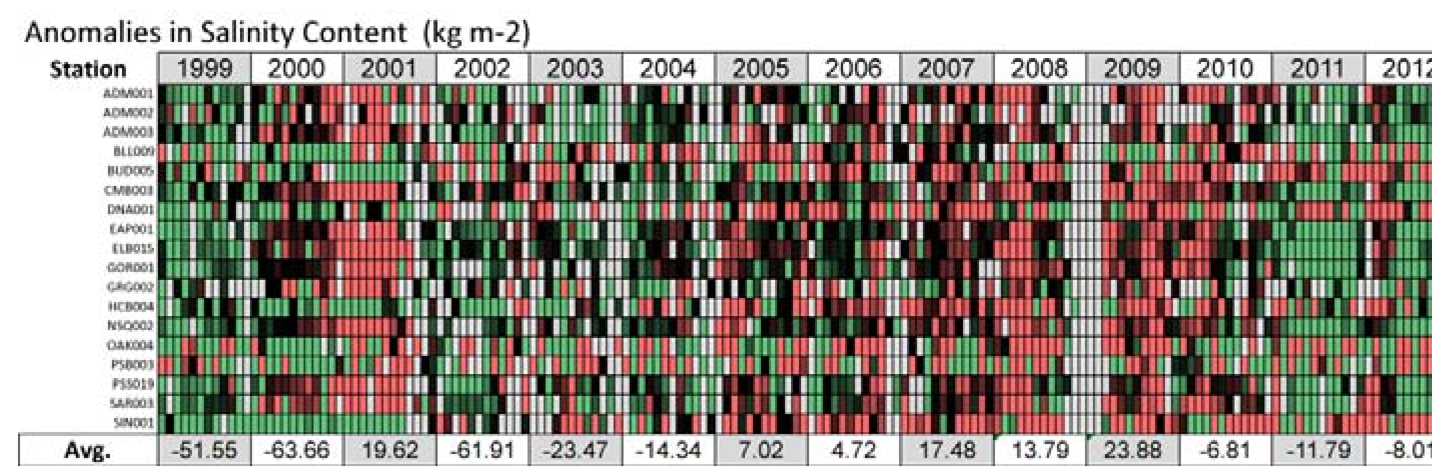


Figure 13. 2012 Puget Sound salinity anomalies for water between 0-50 m depth using a reference baseline established between 1999-2012. Each cell represents a monthly sampling event, each line a station. A shift between green and red indicates saltier (red) or fresher (green) condition black shows expected values, grey missed sampling events.

ii. Dissolved oxygen

Oxygen measurements are used to calculate the amount of oxygen required to saturate portions of the water column that are under-saturated with respect to oxygen. Ecology refers to the total amount of oxygen required to saturate the water column as the “DO deficit” (water that is supersaturated is not included). When DO saturation is high, the deficit is low, and when DO saturation is low, the deficit is high. Over the 1999-2012 period, the DO-deficit for water >20 m was higher during the middle of the decade and has recently fallen below historical levels, implying that overall DO concentrations are higher (Figure 14). Despite regional and monthly variability, the year 2012 stands out to have very low DO deficit values (green) and very favorable oxygen conditions at depth. This recent improvement corresponds well with a change in boundary conditions. The lower annual upwelling in 2012 and cold sea surface temperature anomalies in the North Pacific favor increased oxygen at depth.

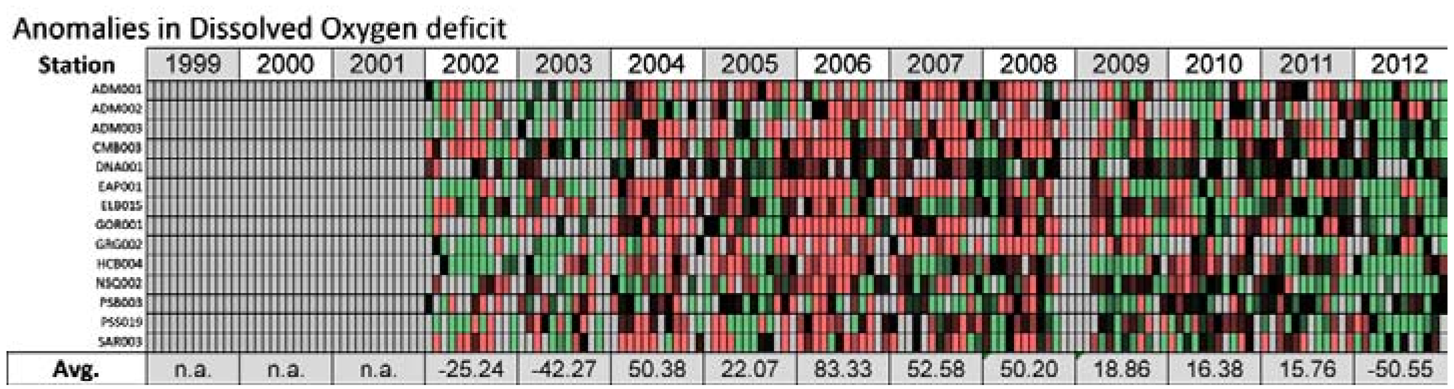


Figure 14. Puget Sound monthly dissolved oxygen (DO) deficit anomalies from 1999-2012 for water > 20 m using a reference baseline established from 1999-2012. Each cell represents a monthly sampling event, each line a station. A shift between green and red indicates saltier (red) or fresher (green) condition black shows expected values, grey missed sampling events.

iii. Nutrients and chlorophyll

Macro-nutrients continue to steadily increase in Puget Sound (Figure 15A), independent of ocean drivers (i.e., PDO, NPGO, and upwelling). Puget Sound-wide nitrate (NO_3) increased at a rate of 3 μM per decade and phosphate (PO_4) by 0.3 μM per decade (Figure 15A). The silica to dissolved inorganic nitrogen (Si:DIN) ratio significantly declined (Spearman Rank Correl. $p<0.05$, $n=14$) over the same decade (Figure 15B). Decreases in the Si:DIN ratio can indicate human nutrient inputs (Harashima, 2007). The decline in the Si:DIN ratio paired with increases in growth limiting macro nutrients favors the growth of non-silicified phytoplankton species such as dinoflagellates. Over the last two years, Ecology’s Eyes Over Puget Sound reports (EOPS; http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html) have documented extensive near-surface blooms of *Noctiluca* and other dinoflagellates in Puget Sound starting as early as February and persisting well into November. Despite large, frequent and extensive near-surface blooms of dinoflagellates, depth integrated chlorophyll *a* concentrations (0-50 m) in Puget Sound have significantly declined at a rate of 80 mg per decade (Spearman Rank Correl. $p<0.05$, $n=13$) (Figure 15B). Coincidently, water clarity has significantly (Spearman Rank Correl. $p<0.05$, $n=13$) increased (not shown here) which independently supports the decline in chlorophyll *a*.

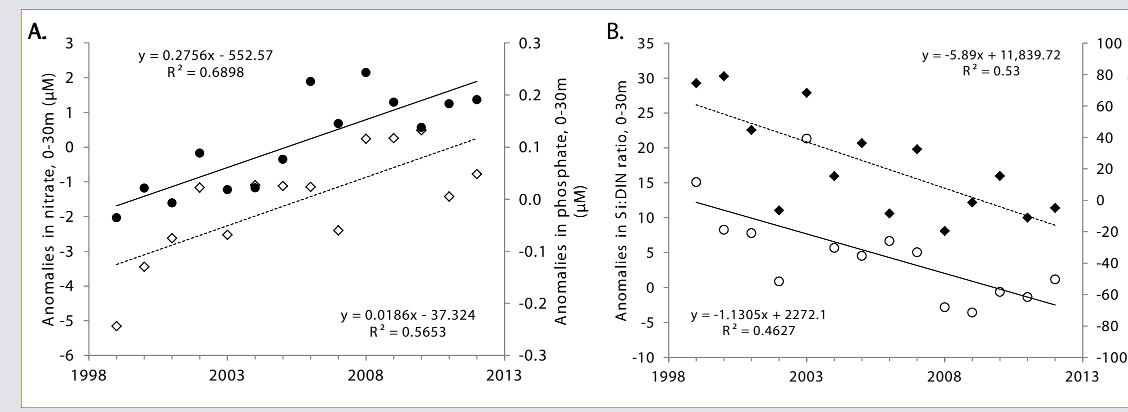


Figure 15. Puget Sound-wide annual anomalies of A. NO_3 and PO_4, and B. Si:DIN and chlorophyll *a* over the period from 1999-2012.

B. Puget Sound profiling buoys

Source: Al Devol, Wendi Reuf (wreuf@u.washington.edu) (UW) and Jan Newton (UW, APL); http://orca.ocean.washington.edu, http://www.nanoos.org

Profiling buoys provide data that can illuminate short-term dynamics and identify water masses. Currently there are six ORCA (Oceanic Remote Chemical Analyzer) moorings in Puget Sound measuring water column properties at high temporal resolution from surface to depth. A high degree of variation in water column properties is seen on a range of scales throughout Puget Sound and Hood Canal. Data from four ORCA moorings are presented here: southern Hood Canal (Twanoh and Hoodsport), north of the Hood Canal sill near Admiralty Reach (North Buoy), and southern Puget Sound (Carr Inlet).

i. Temperature

Temperature data for 2012 are shown in Figure 16. Seasonal trends are observed at each of the moorings, with southern Hood Canal experiencing the warmest surface waters during the summer. Higher surface temperatures and lower bottom water temperatures in southern Hood Canal are due to the strong freshwater stratification, caused by the nearby Skokomish River discharge, which inhibits vertical mixing. By contrast, there are no major freshwater sources into Carr Inlet, and temperatures are more similar to but generally warmer than the North Buoy. Temperatures show strong temporal dynamics, with de-stratification events happening at all locations. However, all stations are unique from each other, notably Twanoh with the highest temperature/strongest stratification and North the lowest and weakest. Carr Inlet showed notably warmer temperature at depth and distributed throughout entire water column during fall, which is unique among these stations.

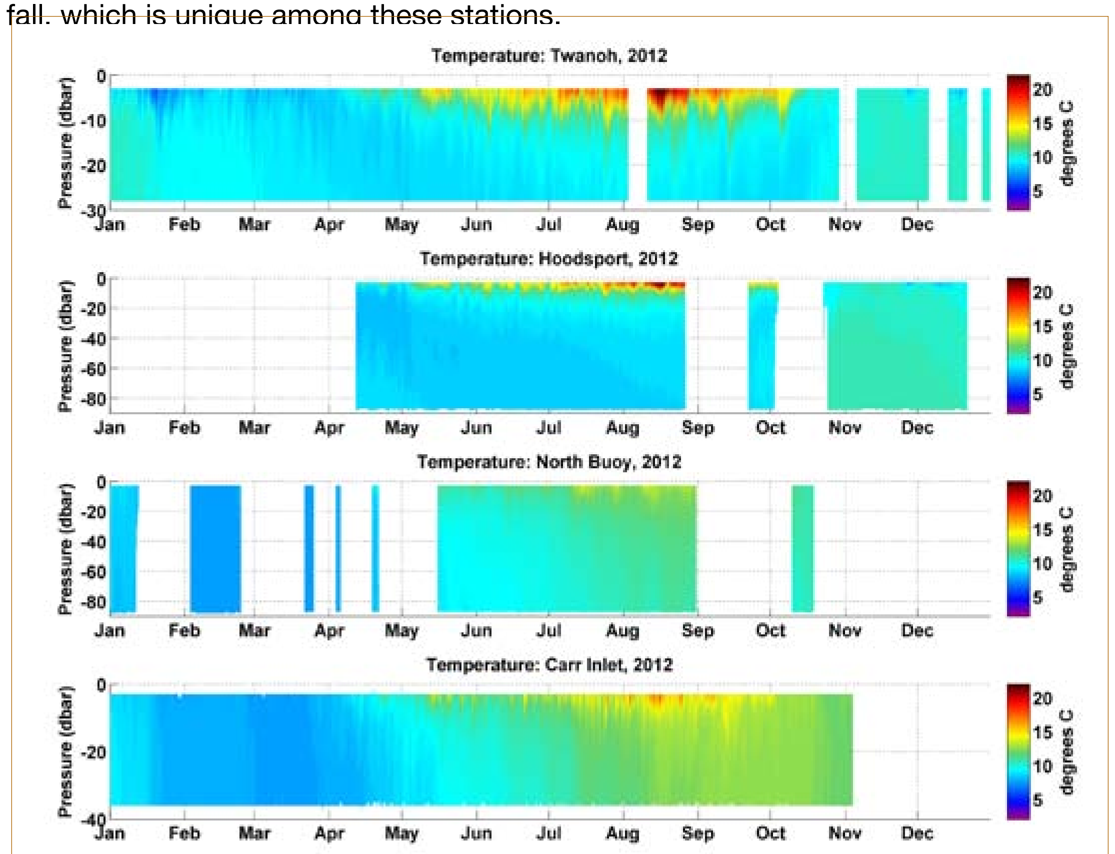


Figure 16. Temperature from the Twanoh and Hoodsport (southern Hood Canal), North Buoy/Hansville (near Admiralty Inlet), and Carr Inlet (southern Puget Sound) moorings for 2012. Pressure in dbars is roughly equivalent to depth meters.

ii. Salinity stratification and blooms

Salinity and chlorophyll *a* concentrations from the Twanoh mooring in southern Hood Canal for 2012 are shown in Figure 17. Strong short-term temporal dynamics on top of seasonal variations are evident in all parameters. Of note is the February spring bloom, an annual observation unique to the southern Hood Canal dataset. Another note-worthy event for 2012 is a very strong sub-surface bloom (10 m or below) in May. Intermittent presence of low salinity waters can also be seen at Twanoh.

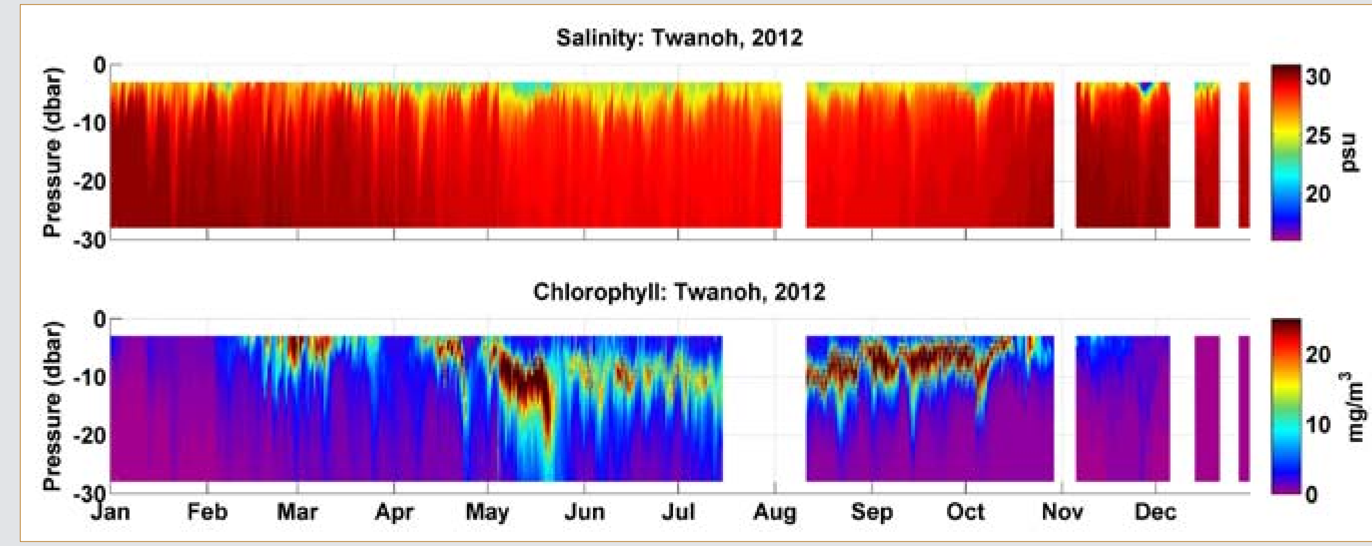


Figure 17. Salinity and chlorophyll a at the Twanoh mooring in southern Hood Canal for 2012. Pressure in dbars is roughly equivalent to depth meters.

iii. Dissolved oxygen

With the exception of southern Hood Canal, hypoxic conditions were not observed at any of the buoy locations during 2012 (Figure 18). The depth of the oxycline is highly variable at all locations. High oxygen pulses are seen at all stations, and vary in length from a few days to several weeks. Associated with the early spring bloom at Twanoh are high surface oxygen concentrations not evident at the other moorings. The Twanoh mooring has revealed periods of hypoxia since it has been in place (2005); however, the hypoxia in 2012 was least intense and shortest in duration over the entire 7 year record. Oxygen data from the most recent three years at Twanoh are shown as a comparison (Figure 19).

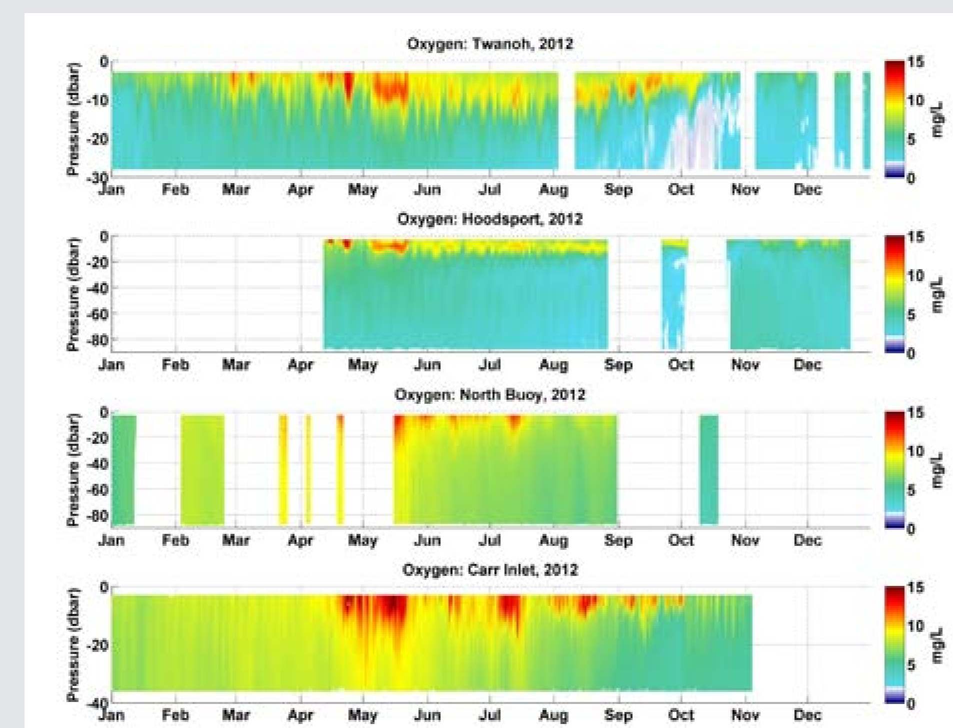


Figure 18. Dissolved oxygen concentrations from the Twanoh and Hoodsport (southern Hood Canal), North Buoy/Hansville (near Admiralty Inlet), and Carr Inlet (southern Puget Sound) moorings for 2012. Pressure in dbars is roughly equivalent to depth meters.

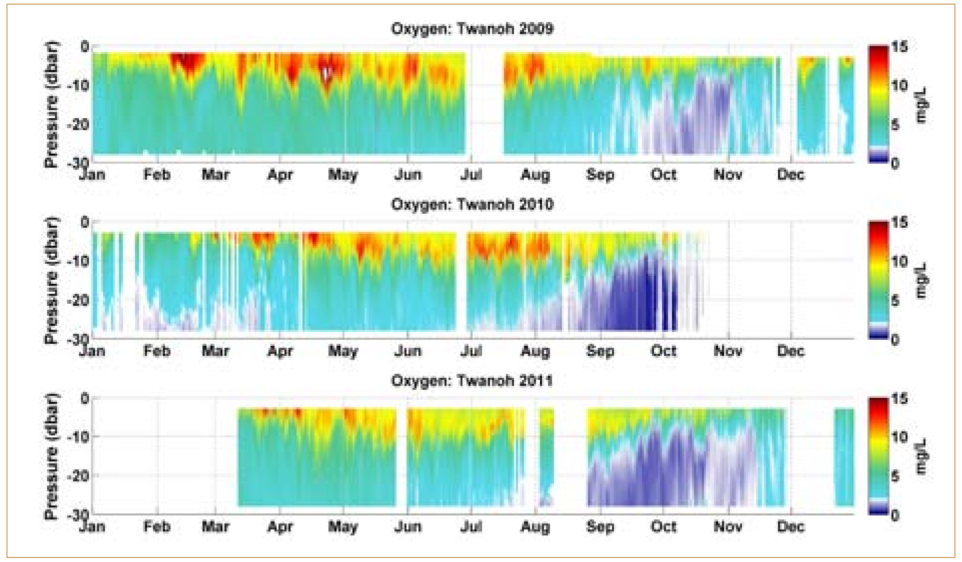


Figure 19. Dissolved oxygen concentrations from the Twanoh mooring for 2009-11. Pressure in dbars is roughly equivalent to depth meters.

C. Main Basin long-term stations

Source: Kimberle Stark (Kimberle.Stark@kingcounty.gov) (KCDNRP); http://green.kingcounty.gov/marine/CTD.aspx, http://green.kingcounty.gov/marine-buoy/

i. Temperature and salinity

Focusing on the Main Basin of Puget Sound, King County collects monthly water column profile data at 12 open water sites. The effects of the cold, wet spring in 2012 can be seen throughout the water column but particularly in surface waters. Water temperatures in 2012 were cooler compared to previous years since 2008, particularly in deep waters (>100 m) in the summer and fall months. Surface temperatures (<30 m), however, were higher than normal from August through October in 2012 due to the warm, dry weather. Fresher waters from the increased freshwater/riverine inputs to the Main Basin were observed at all sampling sites, but the depth over which the fresher waters were mixed was not of the same magnitude as in 2011 (Figure 20A). In 2012, a sharp increase in salinity in the fall is due to the input of oceanic upwelled water – this can be clearly seen at the East Passage site beginning in September (Figure 20B). The pattern shown is representative of other sites.

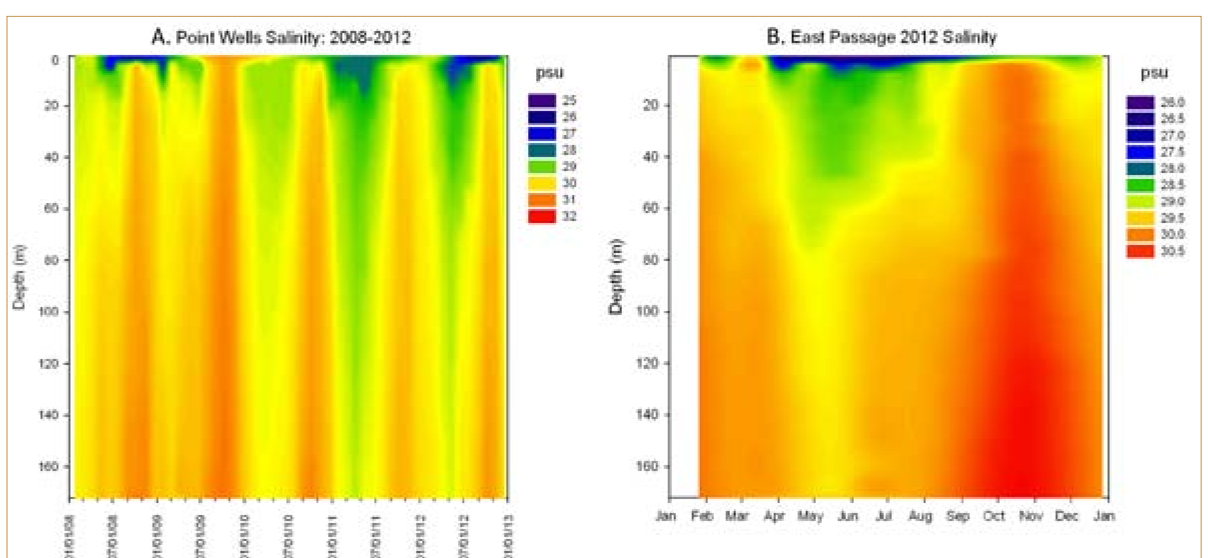


Figure 20. A. Monthly salinity profiles at Point Wells in the Main Basin from 2008-2012. B. Monthly salinity profiles at East Passage in the Main Basin for 2012.

King County also collects monthly temperature and salinity data at 20 marine beach sites located throughout the county. Salinities at beach sites are generally fresher than at sub-tidal sites and vary widely due to proximity to freshwater inputs (e.g., stream outflow or stormwater pipe). Despite the variation between sites, overall, beach salinities were lower in 2012 than seen in previous years, particularly in March and April when a salinity of 16.8 psu was observed. Salinity anomalies for 2012 relative to the long-term average (1999-2011) at Carkeek Park, which is close to a freshwater input, and Alki, away from a known freshwater source, are shown in Figure 21.

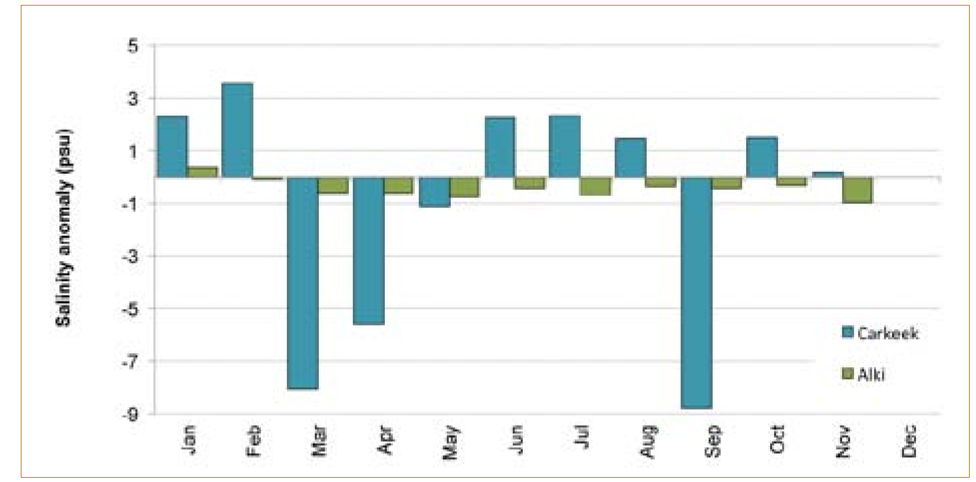


Figure 21. 2012 salinities at two beach sites, Carkeek Park and Alki, relative to a long-term average (1999-2011). Negative values indicate fresher than normal waters.

ii. Dissolved oxygen

Results from monthly sampling at 14 sites in the Main Basin of Puget Sound and 3 in situ moorings indicate that DO levels in 2012 were above 5.0 mg/L throughout the year at all locations, with the exception of Quartermaster Harbor. In 2012, Quartermaster Harbor DO levels dropped below 1.0 mg/L in September, the lowest levels recorded since 2008. Data from the two moorings in Quartermaster Harbor revealed substantial diurnal variation, particularly during the September bloom event (Figure 22).

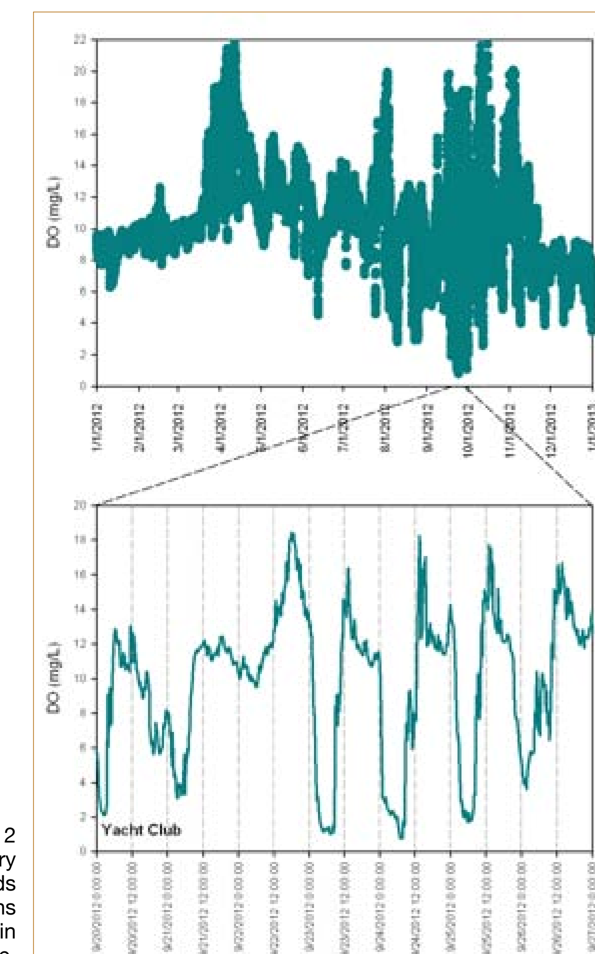


Figure 22. Dissolved oxygen levels for 2012 at inner Quartermaster Harbor recorded every 15-minutes. High values correspond to periods of high primary productivity. Diurnal variations in oxygen levels during a one-week period in September are extreme.

With the exception of Quartermaster Harbor, DO levels in 2012 were similar to the past several years at all King County sites in the Main Basin. An increase in DO levels from primary productivity during the large April and September phytoplankton blooms was evident in the upper 30 m of the water column at most sites (Figure 23). The profiles show lower oxygen deep waters in the late summer and lower oxygen waters throughout the water column in the fall.

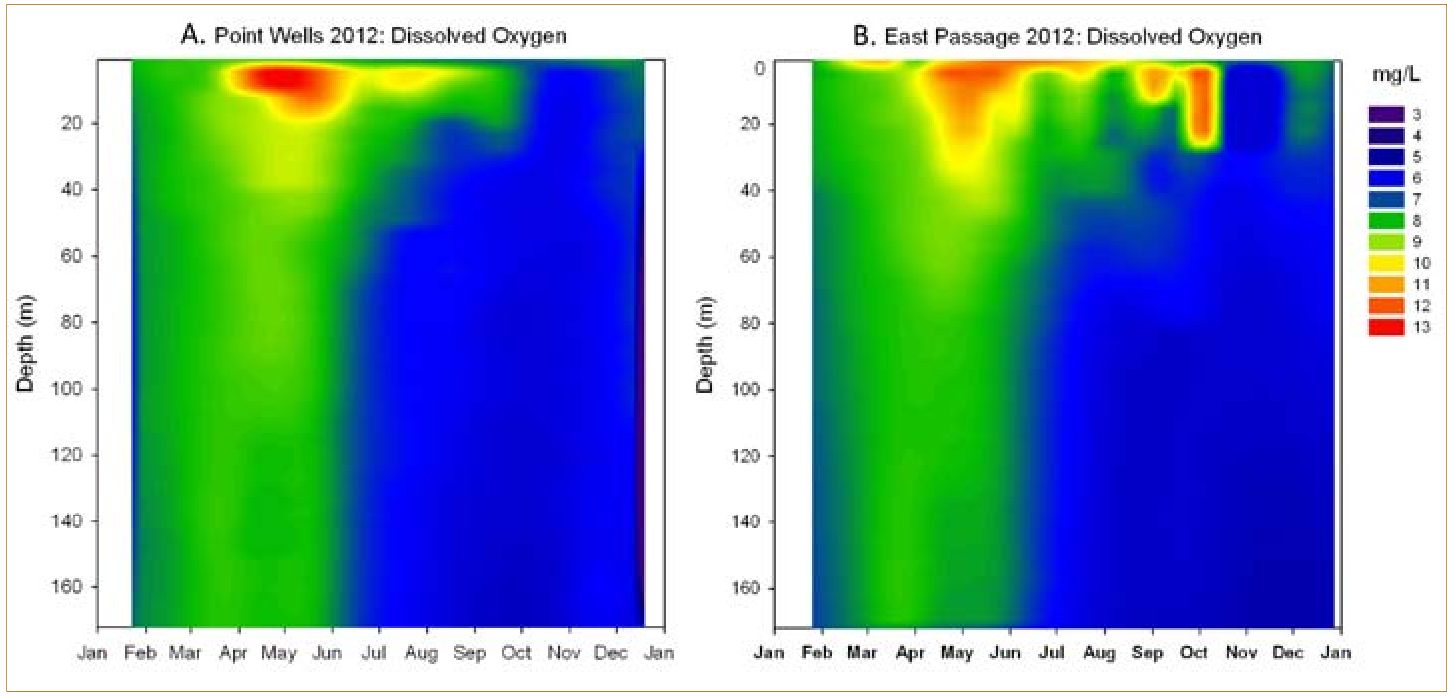


Figure 23. 2012 dissolved oxygen levels at A. Point Wells and B. East Passage in the Main Basin. An increase in oxygen during April and September is evident due to phytoplankton blooms, particularly in East Passage.

iii. Nutrients and chlorophyll

Nutrient levels at the 20 marine beach sites vary considerably and are influenced by proximity to a freshwater source, such as a stream or stormwater outfall. In general, however, nitrate values were lower than normal in April, July, and October 2012 and higher in March and August when compared to previous years (not shown).

Results from monthly sampling at 14 open water sites in the Main Basin of Puget Sound, bi-weekly sampling at a subset of 3 sites from March through October, and 3 in situ moorings reveal nutrient and phytoplankton bloom dynamics in King County waters. The spring phytoplankton bloom occurred at the typical time of year in early April in 2012 and consisted mainly of the diatoms *Chaetoceros* spp. and *Thalassiosira* sp. The 2012 spring bloom was particularly large and lasted throughout most of April (Figure 24A). As a result, there was a reduction in nitrate from surface waters in both April and May (Figure 24B) and a large decrease in silica in May (not shown). The median values of chlorophyll *a* from May to August in 2012 were slightly below values seen in the past 12 years (Figure 24A). Late spring and summer chlorophyll *a* levels show considerable variation and some of this variation might be attributed to temporal sampling limitations. An unusually large bloom in September 2012 (Figure 24A), comprising a variety of both diatoms and dinoflagellates, followed the dry and warm weather in August and September. As a result, September and October nitrate levels were reduced (Figure 24B) well below the long-term average and ammonia levels spiked in October following degradation of the bloom (not shown).

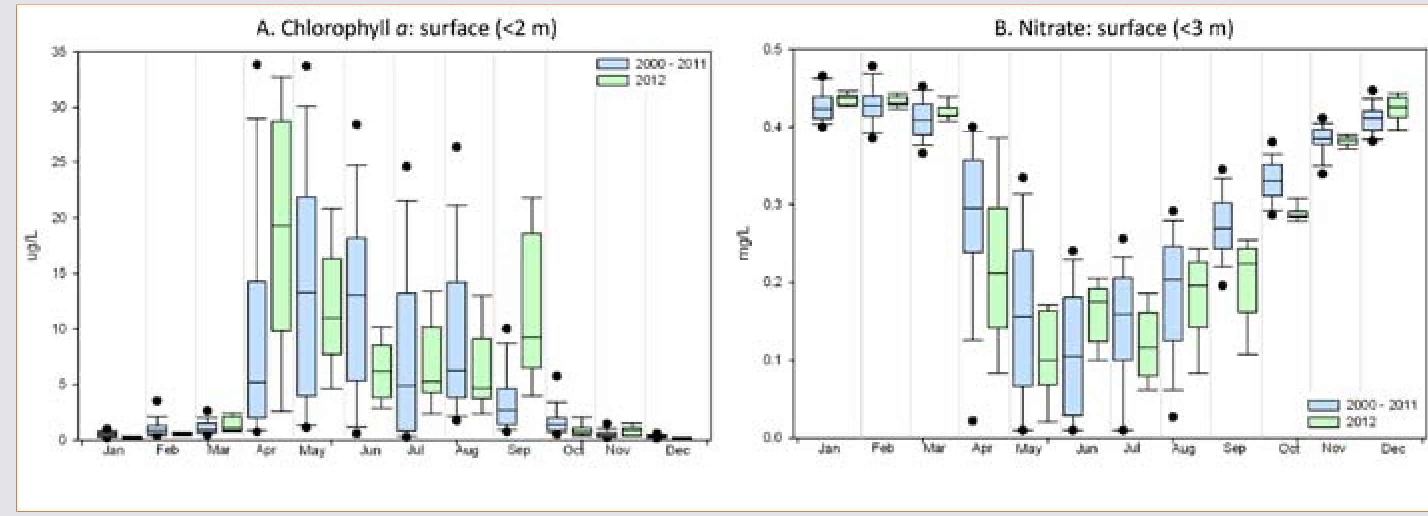


Figure 24. Monthly surface water A. chlorophyll *a* levels and B. nitrate concentrations from 12 sites in the Main Basin for 2012 compared to the long-term average from 2000-2011. The large 2012 April and September blooms are evident as well as the seasonal cycle.

D. Seattle-Victoria surface transects

Source: Brandon Sackmann and Christopher Krembs (ckre461@ecy.wa.gov) (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

The Victoria Clipper (http://www.clippervacations.com/ferry/vesselinformation) regularly transits the 80 miles between Seattle (47.6°N) and Victoria, B.C. (48.4°N), providing an opportunity for observing surface water conditions in the Strait of Juan de Fuca and in Puget Sound's Main Basin. Ecology has equipped the vessel with a Turner Designs C3 fluorometer and a Citadel TS-N thermosalinograph to provide coincident estimates of sea surface temperature and salinity, *in situ* chlorophyll *a* fluorescence, turbidity, and colored dissolved organic matter fluorescence to gain information on surface water dynamics. These measurements provide insights into the variation in waters that may look the same to ferry passengers but are in fact very different at times.

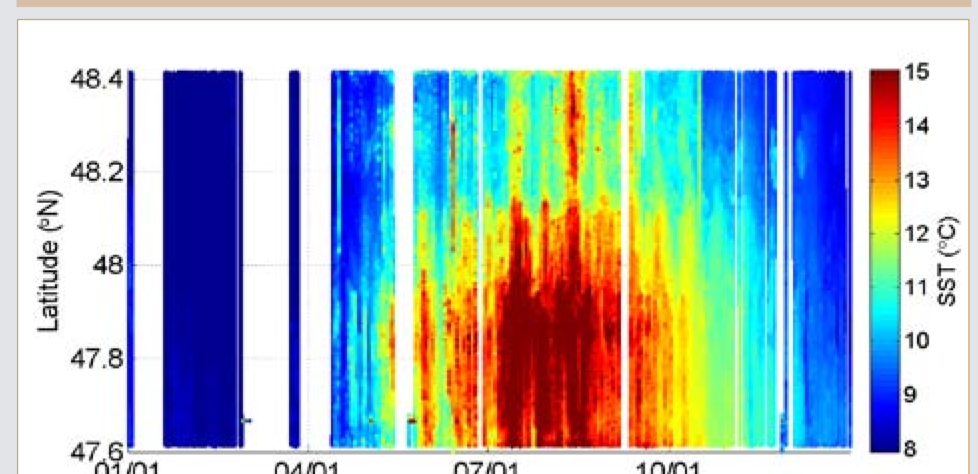


Figure 25. Victoria Clipper sea surface temperature from daily transects in 2012.

i. Temperature and salinity

Strong surface temperature gradients during summer 2012 were observed near the Triple Junction (~47.9°N) with warm, fresh water entering central Puget Sound from Whidbey Basin. At the entrance to Puget Sound in Admiralty Inlet (~48.1°N), large gradients were driven by spring/neap tidal dynamics. Warmer temperatures associated with Fraser River water were evident in the Strait of Juan de Fuca. A period of warmer water in the Straits occurred mid-August of 2012 (Figure 25). In comparison, 2011 had more frequent but less pronounced intrusions.

ii. Chlorophyll

The spring phytoplankton bloom in Central Puget Sound began a few weeks earlier in the year compared to 2011. In mid-October 2012, strong southerly winds quickly mixed phytoplankton biomass to greater depth, marking a fall-transition that was more abrupt than in 2011. Phytoplankton blooms in the Strait of Juan de Fuca appeared weaker in 2012 compared to 2011 (Figure 26). Summer 2012 transects revealed two chlorophyll *a* clearing events (i.e., sudden drop in chlorophyll *a*) in the Main Basin. The first clearing event in June occurred in conjunction with an extensive *Noctiluca* bloom along the transect from Seattle to Everett (Figure 27). Interestingly, this pattern was also observed in 2011 when a clearing event occurred in conjunction with a June *Noctiluca scintillans* bloom. *Noctiluca* is a heterotrophic dinoflagellate that is frequently associated with eutrophied coastal environments (Vasas et al., 2007). In both 2011 and 2012, chlorophyll *a* dropped within days of the *Noctiluca* bloom occurring and cells had visibly accumulated at the surface during calm wind conditions.

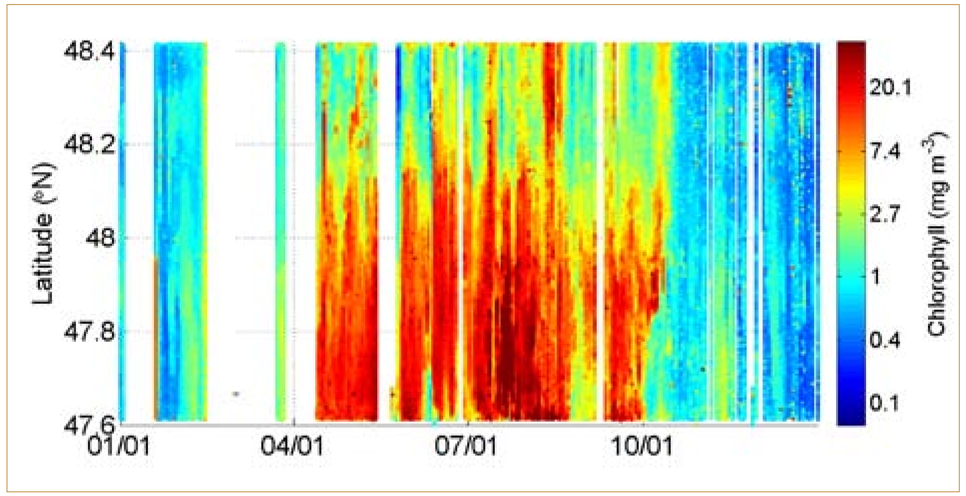


Figure 26. Victoria Clipper chlorophyll a from daily transects in 2012.

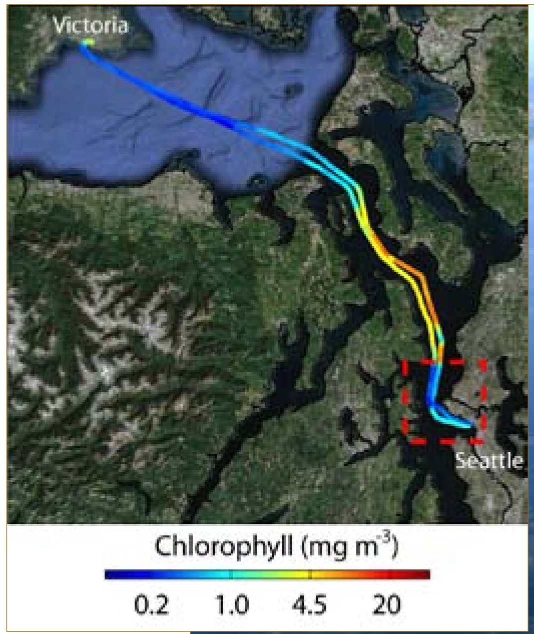


Figure 27. A transect of Victoria Clipper chlorophyll a data during 2012 showing the area of the clearing event between 47.6-47.8° N along the ferry transect.

Eyes over Puget Sound aerial observation flight documented large Noctiluca blooms in the Central Basin, June 2012. Photo credit: Christopher Krembs (Ecology)

Snapshot surveys take place over a short period of time and can provide intensive observations in select regions of interest. When interpreted in the context of more frequent long-term observations, snapshot surveys can reveal processes and variations in water conditions that would not otherwise be detected.

E. Snapshot surveys

i. Salish Sea tribal canoe journey surface survey:

Source: Eric Grossman (egrossman@usgs.gov) (U.S. Geological Survey) and Sarah Grossman (sgrossman@swinomish.nsn.us) (Swinomish Indian Nation); http://www.usgs.gov/coastsalish

The Salish Sea tribal canoe journey offers a unique annual view throughout much of the sea during summer. July 2012 was the fifth year of sampling for the Tribal Journey Water Quality Project (TJWQP). In 2012, 23,000 surface-water measurements were collected from traditional canoes at ~20 m intervals across the Salish Sea from Comox, B.C. to Squaxin Island, WA (Figure 28). Surface water temperature ranged from 10.2ºC in the Strait of Juan de Fuca (JDF) to 26.0ºC along the west Georgia Strait. The mean surface water temperature value of 19.5ºC in 2012 was higher in 2012 compared to previous TJWQP values for 2008 and 2010. Surface water temperatures were moderately high in San Juan basin and Whidbey Basin (WB) where the mean (and maxima) values were 15.3ºC (17.8ºC) and 15.6ºC (19.0ºC), respectively. Mean basin salinity ranged from 12.4 PSU in WB to 28.8 PSU in the JDF and was generally lower in 2012 compared to all previous TJWQP years. Median pH ranged from a low of 7.8 in South Puget Sound to a high of 8.4 in WB. Mean values of dissolved oxygen in each basin were generally high in 2012, but minimum values were lowest in South Central and South Puget Sound. Turbidity generally reflected river sources as observed across the Puyallup River plume which ranged 20-50 FNU and extended across Commencement Bay although high turbidity was also measured along southern WB and North Central Puget Sound offshore of Shilshole Bay. The extent of marine surface water temperatures observed and exceeding 16ºC, a concern for aquatic life uses, highlight the need to better understand river conditions and their influence on the Salish Sea. For example, 40% of WB temperatures and 99.5% of west Georgia Strait temperatures measured were above 16ºC (74% above 19ºC) even though runoff in 2012 was 1.5-2.0 times greater than the historical mean due to high snowpack/glacier-melt. The cold source of water from melting snowpack and glaciers which buffers temperatures and provides thermal refugia for temperature-sensitive fish is projected to decrease with expected climate change.

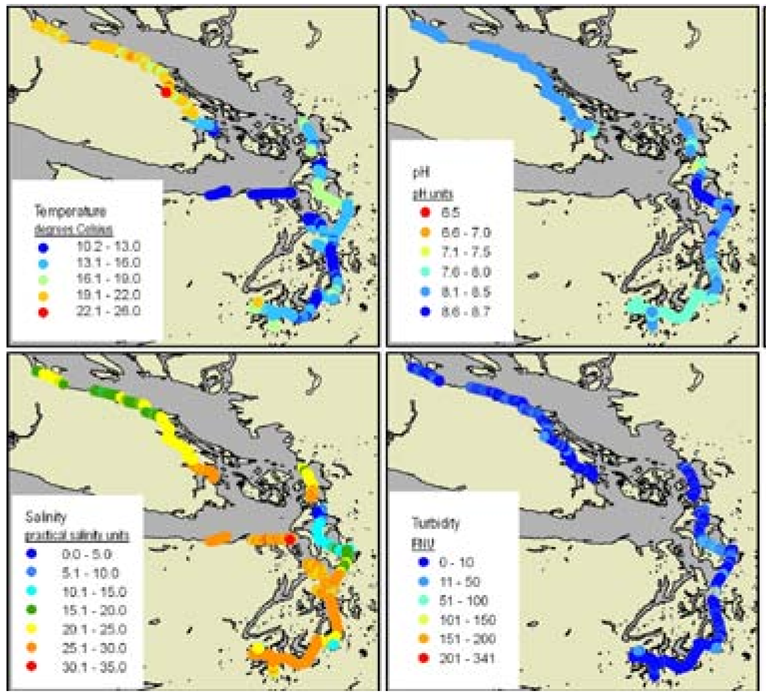


Figure 28. Map showing the results of the July 2012 tribal journey water quality project.

ii. San Juan Channel/Juan de Fuca fall surveys

Source: Jan Newton (newton@apl.washington.edu) (APL, UW) and Kali Williams (UW); http://www.nanoos.org

In addition to the annual UW Puget Sound PRISM-NANOOS cruise, which did not happen during 2012 due to ship maintenance issues, UW has sponsored another time-series based out of the UW Friday Harbor Laboratories since 2004. These cruises are conducted by undergraduate research apprentices participating in the UW "Pelagic Ecosystem Function" course taught at the Friday Harbor Laboratories. Each fall two stations are sampled: (i) North Station in San Juan Channel, a station with strong tidal mixing that is influenced by Fraser River flow when seasonal winds push the plume south, and (ii) South Station just south of Cattle Pass and in the Strait of Juan de Fuca, a stratified regime with estuarine outflow at the surface and oceanic inflow in the deeper layer. The oceanic waters typically shift from being influenced by upwelling to downwelling during the fall, associated with the seasonal wind shift.

Water properties averaged over the top 20 m reveal interannual patterns between 2004 and 2012. While exceptions are found, typically El Niño years have warmer than average surface temperatures and La Niña years exhibit lower surface temperatures (Figure 29). However, fall 2012 (which was neither El Niño nor La Niña) exhibited some of the warmest (late September to early October) and coldest (mid to late October) surface waters in the nine-year record. Early fall 2012 had unseasonably sunny and warm weather which may have resulted in surface heating, accounting for the warmer early temperatures. The source of the very cold waters during mid to late October 2012 may have been associated with an oceanic intrusion at depth at the South station that mixed and cooled surface waters throughout the area. This is indicated by data for the 60-80 m deep layer (not shown). Deep temperatures at the North station showed a similar pattern as seen in the surface temperatures. However, at the South station, while deep temperatures were average for that station during mid to late October (8.6° C), the temperature was almost a degree cooler (7.7° C) on October 10, 2012, preceding the observation of abnormally cool surface waters at both the South and North stations by about a week. This deep water mass had high salinity, low oxygen and would be presumed to have high pCO_2 and low pH. These observations may indicate an amplified influence of incoming deep oceanic waters on surface waters in well-mixed estuarine environments.

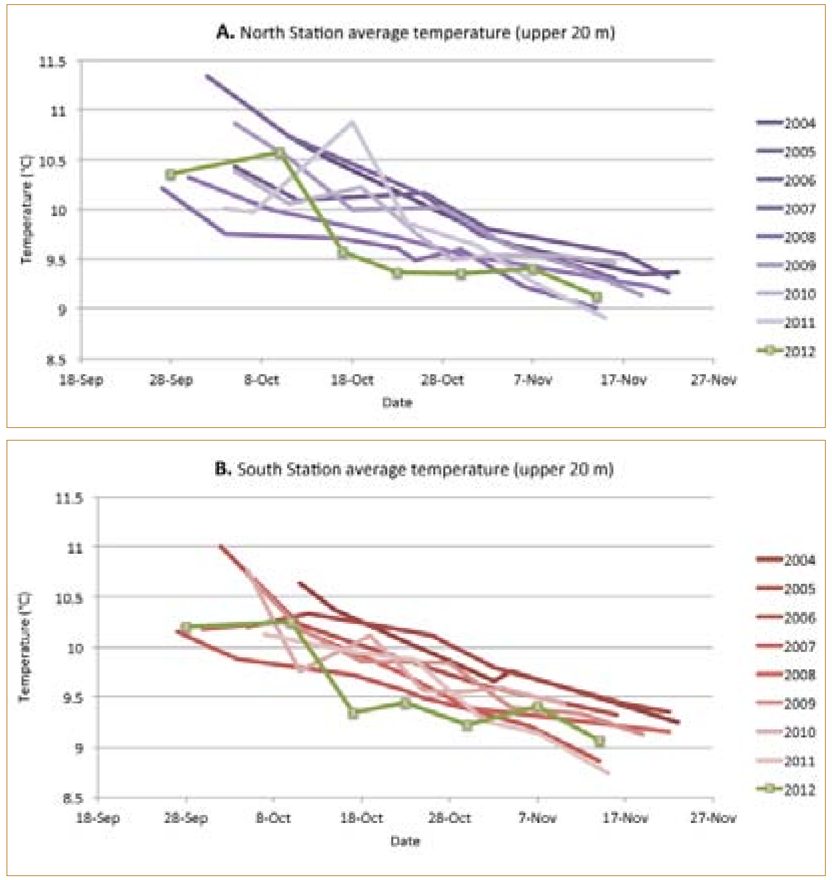


Figure 29. Average temperature in the upper 20 m of the water column from CTD profiles at A. North Station in the San Juan Channel and B. South Station in the Strait of Juan de Fuca from 2004-2012. Red lines indicate El Niño years, blue lines La Niña years, and gray lines ENSO-neutral years.

Surface chlorophyll plots (Figure 30) reveal larger than average blooms at both stations though particularly so at the North station during early fall, consistent with the atypically warm, sunny weather during that part of 2012. These high concentrations in early 2012 were confirmed by phytoplankton cell counts that were also the highest observed in this nine-year record.

iii. Hood Canal oxygen inventory

Source: Mark Warner (warner@u.washington.edu) (UW) and Jan Newton (UW, APL); http://www.hoodcanal.washington.edu/observations/historicalcomparison.jsp

The seasonal pattern in dissolved oxygen in the main stem of Hood Canal is shown in Figure 31. Relative to the full data record of 29 years representing the 1950s, 1960s, 1990s and 2000s, the data for 2012 showed relatively high oxygen concentrations, which was also seen in the buoy data from Twanoh (Figure 18). The last observation in 2012, which occurred in late September, was the exception when values aligned more with the average. These data follow 2011, which was a very average year. There were no cases of fish kills reported in Hood Canal during 2012, as would be expected. The source of the high variation during spring is related to flushing strength driven by internal and external climate and seawater conditions. The low variation during fall is likely due to the consistency of oceanic intrusion oxygen concentrations. This data time series is unfortunately no longer funded past 2012.

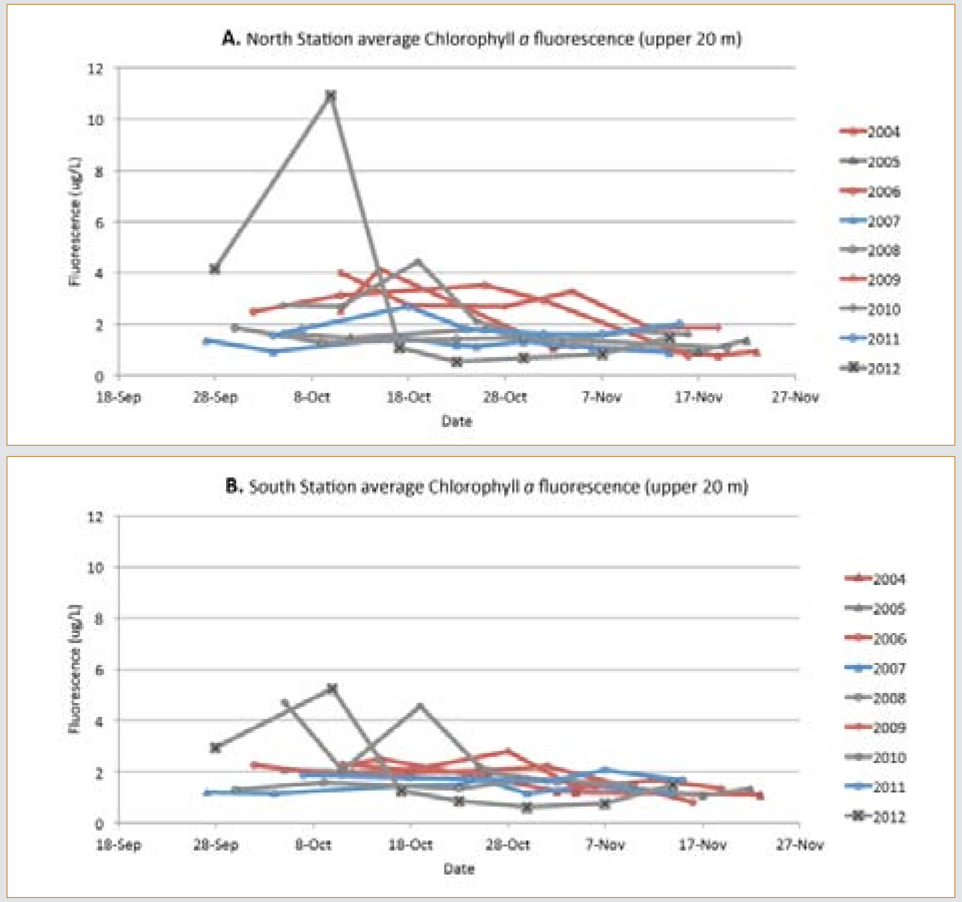


Figure 30. Average chlorophyll *a* fluorescence in the upper 20 m of the water column from CTD profiles at A. North Station in the San Juan Channel and B. South Station in the Strait of Juan de Fuca from 2004-2012. Red lines indicate El Niño years, blue lines La Niña years, and gray lines ENSO-neutral years.

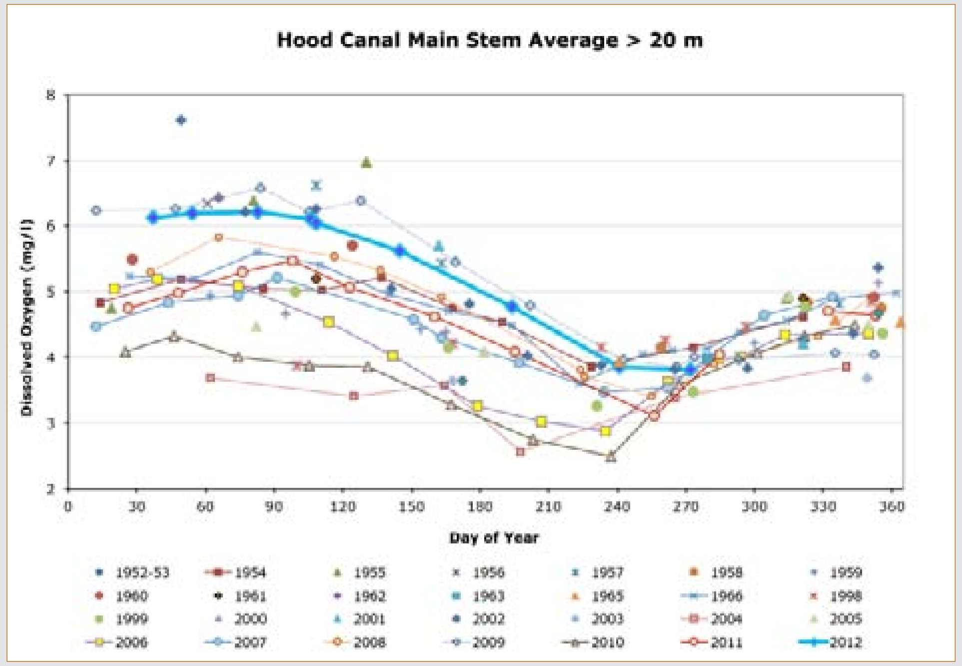


Figure 31. The average dissolved oxygen concentration in the water below 20 m depth in the region between Dabob Bay and the Great Bend (PRISM Station 11) plotted versus the day of the year. The data from the 1950s and 1960s are from Collias et al., 1966. The data from the 1990s and some of the 2000s are from the University of Washington PRISM program. The data from much of the 2000s are from the Hood Canal Dissolved Oxygen Program; PRISM and HCDOP data are available at http://www.nanoos.org.

The Blue Ribbon Panel on ocean acidification

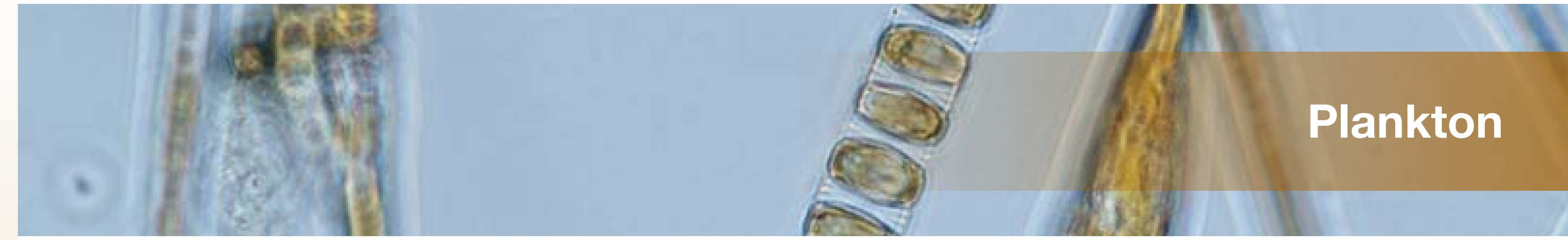
Ocean acidification (OA) is a threat that is only beginning to be addressed in Puget Sound (Feely et al. 2010). Each year approximately 25% of the excess carbon dioxide in the atmosphere resulting from human activities is absorbed by the oceans, resulting in a lower pH and carbonate ion concentration. Estuarine processes, both natural and human-mediated can also increase the carbon dioxide content and lower the pH of marine waters. Coastal upwelling also brings deeper, more corrosive waters into the Strait of Juan de Fuca and, ultimately, into the deep waters of the Main Basin and Hood Canal. Thus, Puget Sound is influenced by a variety of drivers of OA, which has ramifications for marine food webs generally, and shellfish in particular. Many shellfish species secrete $CaCO_3$ shells, a process which is impeded under corrosive conditions.

Recognizing the threat to Washington's shellfish industry, its tribal communities, and its broader marine environment, Washington State Governor Gregoire convened a "Blue Ribbon Panel on Ocean Acidification" in February 2012. The Blue Ribbon Panel was composed of leading tribal, state, federal and local policy makers; legislators, scientific experts; public opinion leaders; and industry representatives. The charge to the Panel was to: review and summarize the current state of scientific knowledge about OA; identify the research, monitoring and modeling needed to increase scientific understanding and improve resource management; develop recommendations to respond to OA and reduce its harmful causes and effects; and identify opportunities to improve coordination and partnerships and to enhance public awareness and understanding of OA and how to address it.

The Panel released its findings in November 2012. It's recommendations were contained in "Ocean Acidification: From Knowledge to Action" (*https://fortress.wa.gov/ecy/publications/publications/1201015.pdf*). The Panel also released a "Scientific Summary of Ocean Acidification in Washington State Marine Waters" (*https://fortress.wa.gov/ecy/publications/publications/1201016.pdf*) detailing what is known, not known and important to know regarding ocean acidification in Washington marine waters. This latter document summarizes driving factors, including the upwelled high-CO_2 waters, nutrient and organic carbon loads, freshwater inputs, and acidifying gases and wastes. Regionally, very little is known about the relative contributions of these factors, but we do know that the system is quite variable, with variation due to season, depth, proximity to the ocean, basin depth and mixing, regional loads, etc. Biological effects, both on species and communities, were also evaluated using the literature available, which is sparse for Washington State.

As of April 2013, the Panel recommendations are being evaluated by the Legislature for funding, including recommendations for research and monitoring. The Panel recommended to "Establish an expanded and sustained ocean acidification monitoring network to measure trends in local ocean acidification conditions and related biological responses." They recognized the need to enhance and sustain existing elements and assets as well as to establish new monitoring stations for integrated co-located physical, chemical, and biological data to evaluate changing chemical conditions and biological responses. Further, the monitoring sites established by shellfish growers should be expanded and sustained. It was envisioned that the effort would include both mobile and fixed platforms and need to cover all of Washington's marine waters: the outer coast, the Strait of Juan de Fuca, greater Puget Sound, and the Columbia River estuary.

Authors: Richard Feely (NOAA, PMEL) and Jan Newton (UW), Blue Ribbon Panel Members



Plankton

Marine phytoplankton are microscopic algae that form the base of the marine food web. They are also very sensitive indicators of ecosystem health and change. Because they respond rapidly to a range of chemical and physical conditions, phytoplankton community composition can be used as an indicator of deteriorating or changing ocean conditions that can affect entire ecosystems.

A. Marine phytoplankton

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov) and Kimberle Stark (KCDNRP); http://green.kingcounty.gov/marine/photos.aspx

King County has monitored three stations for phytoplankton at biweekly intervals from April to October since 2008 as an extension of the Marine Ambient Monitoring Program. Point Jefferson and East Passage are deep water stations at the north and south end of the Puget Sound Main Basin, respectively, whereas Dockton in Quartermaster Harbor is a shallow station near the entrance to an embayment with poor tidal flushing. To date, sample analysis has focused primarily on taxon identification and relative abundances.

Diatoms typically comprise the most abundant and diverse group of primary producers in Puget Sound. Nine chain-forming diatom genera and five dinoflagellate genera (primarily photosynthetic) were most commonly encountered in 2012 (Figure 32). Due to its large size, the common dinoflagellate *Noctiluca scintillans* did not meet criteria for high relative abundance, despite blooms occurring in 2012 that visibly colored the water.

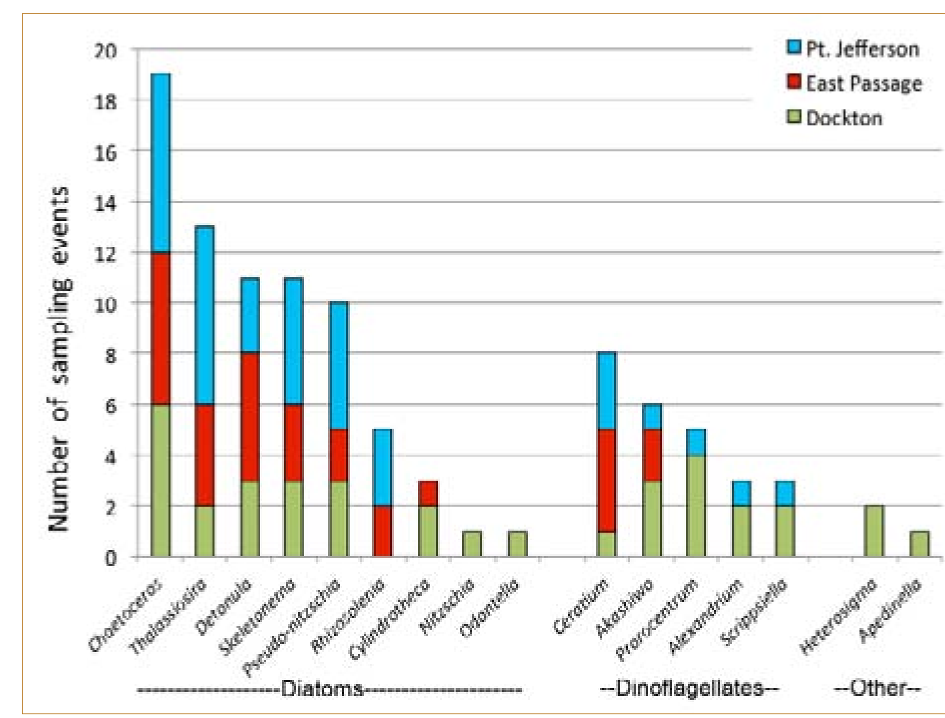


Figure 32. Most abundant phytoplankton genera encountered in 2012. These genera were considered abundant (categorized as common, subdominant or dominant based on relative cell numbers) for the number of sampling events shown.

The 4-year time series from 2008-2011 reveals a distinct seasonal pattern in the proportion of diatom genera in a given sample relative to all genera identified for each station (Figure 33). In 2012, abundant early spring blooms in the Main Basin were immediately followed by a period of increased diatom diversification. The unusually sharp drop in the proportion of diatom genera during the summer of 2012 is consistent with the particularly dry and warm weather observed during those months – conditions that generally favor dinoflagellate populations as these organisms are less dependent on surface nutrients. Dinoflagellate genera were especially prevalent during early and late summer in the south Main Basin and in Quartermaster Harbor, with remarkably conspicuous late blooms of *Akashiwo sanguinea* that colored the water red. In the fall, diatom populations quickly recovered following nutrient inputs related to upwelled oceanic waters and higher than normal precipitation.

Nitrogen/phosphorus molar ratios plotted alongside the proportion of diatom genera sampled for 2012 (Figure 33) suggest that nitrogen limitation may be an important driver for seasonal changes in species composition. High silica:nitrogen ratios observed throughout the season indicate no silica limitation (not shown); silicic acid is an essential nutrient for diatoms.

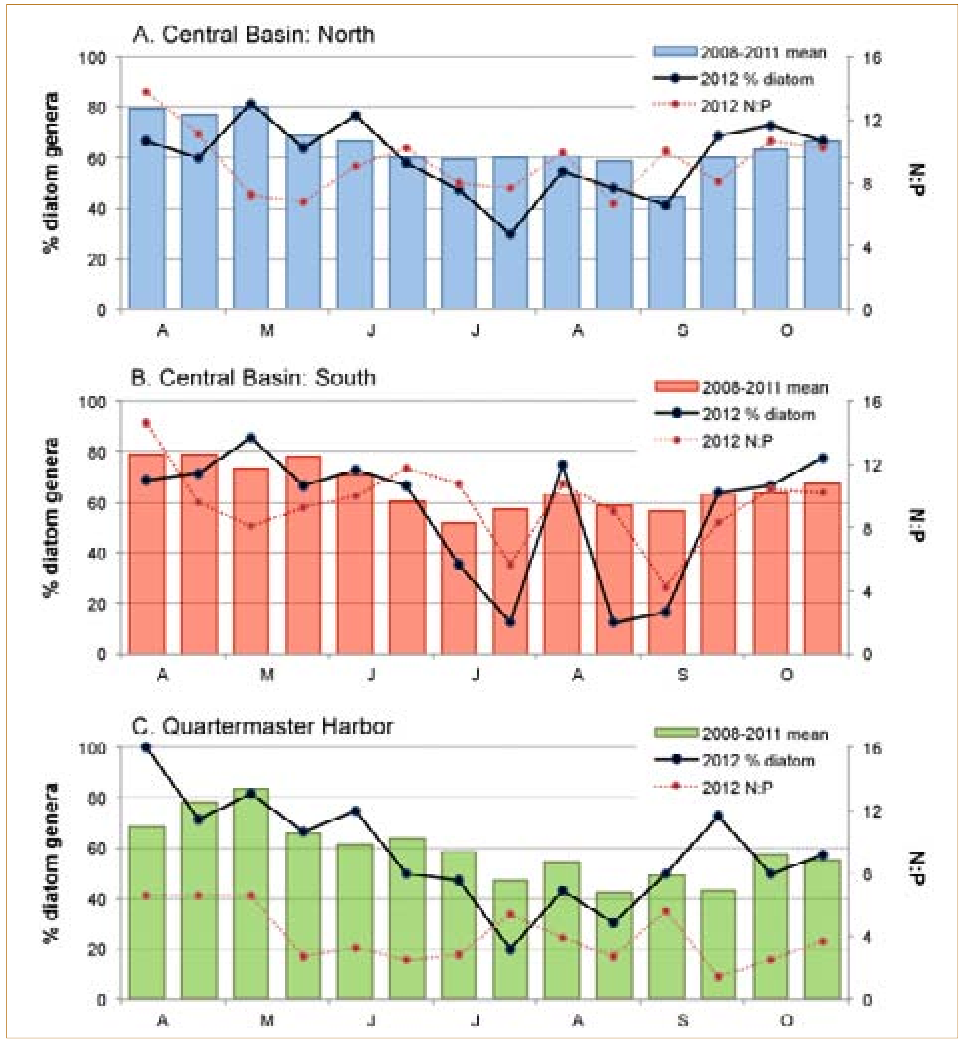


Figure 33. Seasonal changes in the proportion of diatom genera identified in samples collected at Point Jefferson (Main Basin: North), East Passage (Main Basin: South) and Quartermaster Harbor. Bars show 2008-2011 monthly mean values; lines indicate 2012 values. N:P molar ratios are for surface waters (<2 m), where N is nitrate+nitrite nitrogen and P is orthophosphate phosphorus.

Ceratium fusus.
Photo credit: Gabriela Hannach

Akashiwo sanguinea.
Photo credit: Gabriela Hannach

Thalassiosira punctigera.
Photo credit: Gabriela Hannach

B. Harmful algae

Harmful algal blooms (HABs) are natural phenomena caused by rapid growth of certain kinds of algae, resulting in damage to the environment and/or risk to human and ecosystem health. Many HAB species produce toxins that can cause illness or death in humans if contaminated shellfish are consumed. Other HABs can cause fish kills

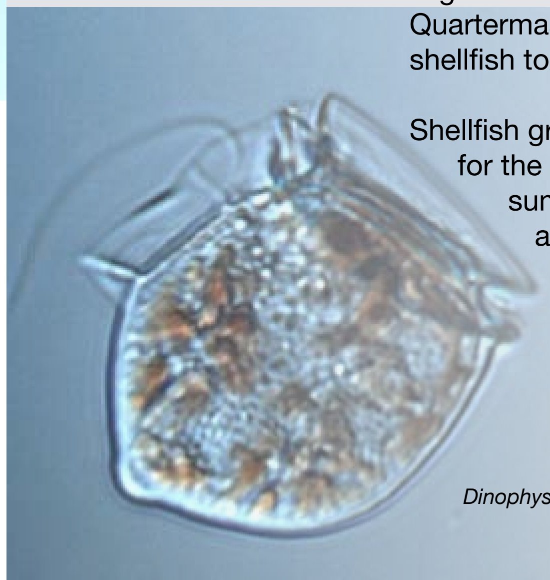
i. SoundToxins

Source: Teri King (soundtox@uw.edu) and Kate Litle (WSG), and Vera Trainer (NOAA, NWFSC); www.soundtoxins.org

The "SoundToxins" program samples phytoplankton at key locations throughout Puget Sound, reporting cell concentrations of *Alexandrium* spp.*, Dinophysis* spp.*, Heterosigma* sp.*,* and *Pseudo-nitzschia* spp. This provides an early warning system for the Washington State Department of Health to prioritize shellfish toxin analysis and timely information to shellfish and finfish producers and researchers. Active monitoring sites in 2012 were: Budd Inlet, Discovery Bay, Dolphin Bay, East Sound, Fort Worden, Manchester, Mystery Bay, Nisqually Reach, North Bay, Oakland Bay, Penn Cove, Penrose State Park, Port Townsend, Quartermaster Harbor, Quilcene Bay, Rosario Beach, Sequim Bay, Spencer Cove, Totten Inlet, and Port Susan. Sampling stations are monitored weekly from April to October and biweekly during the winter months.

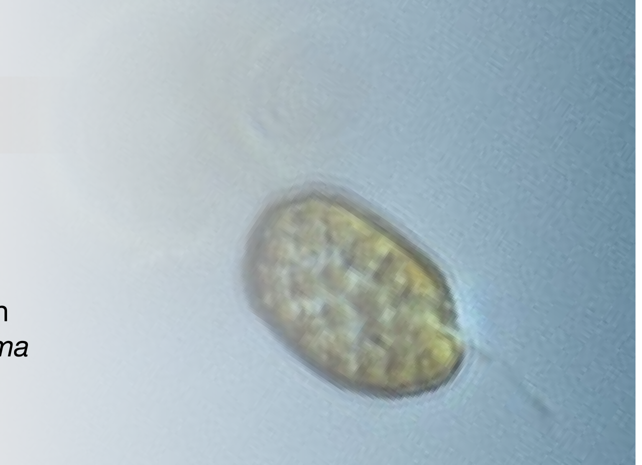
Alexandrium spp. counts were low or absent from most of the sampling locations throughout 2012 with the exceptions being Discovery Bay, Sequim Bay and Quartermaster Harbor. At the Discovery Bay site, *Alexandrium* spp. cell counts increased rapidly in August and September reaching levels >1.3 million cells/L on September 19, 2012. The Discovery Bay shellfish growing area was closed during this time because of the presence of paralytic shellfish toxins. At the Sequim Bay monitoring site, *Alexandrium* spp. appeared as early as mid-June and then increased in abundance to 30,000 cells/L in August and maintained a presence of a few thousand cells/L until early December. Sequim Bay encountered numerous shellfish growing area closures due to toxins in 2012. *Alexandrium* spp. started to appear in Quartermaster Harbor in April and steadily increased throughout the summer with a full bloom (i.e., 1.1 million cells/L) occurring on September 3, 2012. *Alexandrium* spp. lingered in Quartermaster Harbor until late October and disappeared in November. Quartermaster Harbor was closed to the harvesting of shellfish due to high paralytic shellfish toxin concentrations.

Shellfish growing area closures due to toxins produced by *Dinophysis* spp. occurred for the first time in Puget Sound in 2011, resulting in enhanced monitoring in the summer of 2012. *Dinophysis* spp. was identified at all monitoring stations at least once throughout the year with cells appearing in mid-April and maintaining a sustained presence until early December. Quartermaster Harbor had the highest observed level of *Dinophysis* spp. at 20,000 cells/L on July 9, 2012, followed by Sequim Bay in November 9, 2012 with a count of 13,000 cells/L (Figure 34).



Dinophysis. Photo credit: Gabriela Hannach

Heterosigma sp. had variable presence among the various monitoring locations in 2012. Sites where *Heterosigma* sp. was present include: Quartermaster Harbor which experienced a high of 3,000 cells/L in early July; Port Townsend that saw *Heterosigma* sp. as early as February 23, 2012, with cells present through early November; Discovery Bay and Fort Worden in June; and Manchester in May and August of 2012.



Heterosigma.
Photo credit: Gabriela Hannach

Pseudo-nitzschia spp. was common throughout Puget Sound in 2012, including both large and small species. The highest cell concentrations were observed in Sequim Bay, Quartermaster Harbor, and Penn Cove at >200,000 cells/L in early May and August. Despite the high cell counts, no domoic acid-related shellfish closures occurred in Puget Sound during 2012.

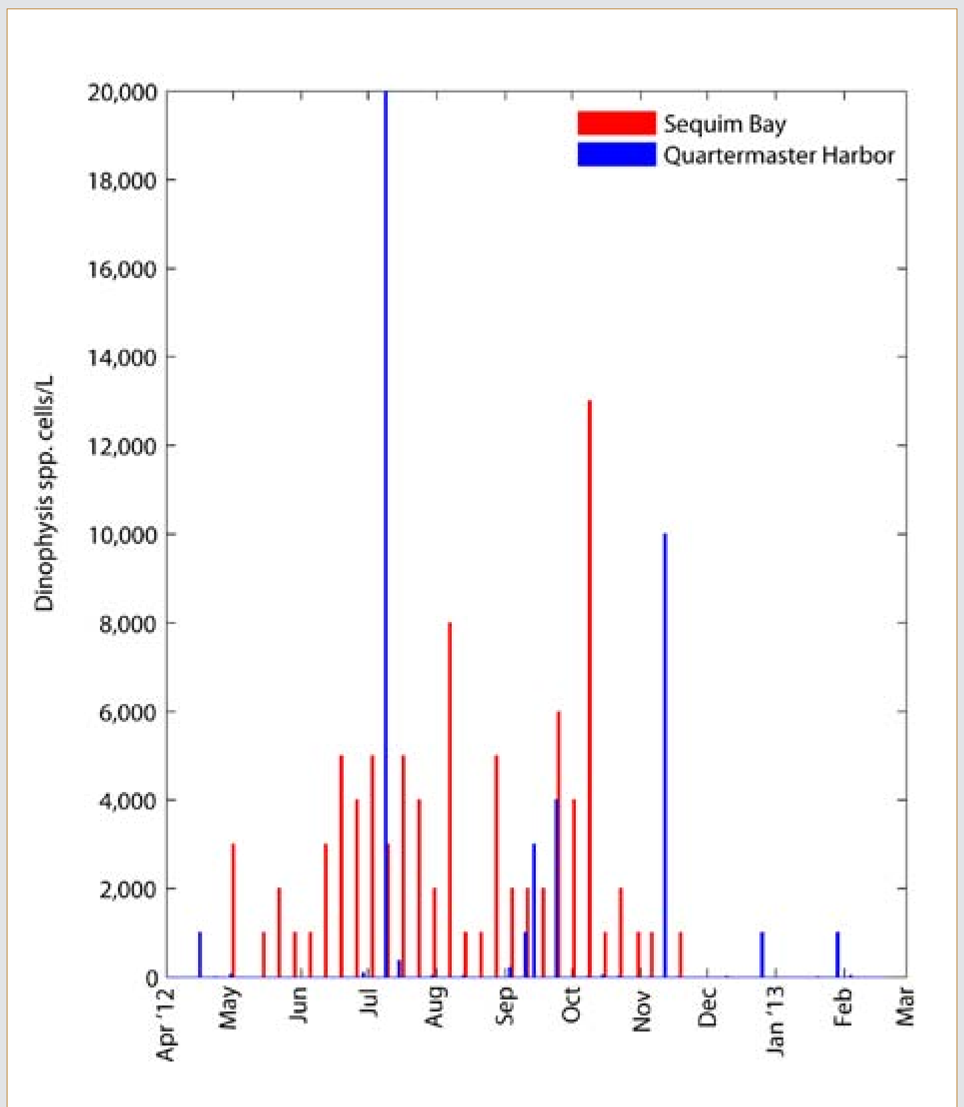


Figure 34. *Dinophysis spp.* abundance in Sequim Bay and Quartermaster Harbor during 2012.

Alexandrium spp. form dormant cysts that overwinter on the seafloor and provide the inoculum for toxic blooms the following summer when conditions become favorable again for growth of the motile cell. "Seedbeds" with high cyst abundances correspond to areas where shellfish frequently attain high levels of toxin in Puget Sound. Cyst surveys are a way for managers to determine how much "seed" is available to initiate blooms, where this seed is located, and when/where this seed could germinate and grow.

ii. Alexandrium species cyst mapping

Source: Cheryl Greengrove (cgreen@uw.edu) and Julie Masura (UWT), and Stephanie Moore (NOAA, NWFSC and UCAR); http://www.tiny.cc/psahab

The PS-AHAB (Puget Sound *Alexandrium* Harmful Algal Bloom) project, funded by NOAA's Ecology and Oceanography of Harmful Algal Blooms program, seeks to understand environmental controls on the benthic (cyst) and planktonic life stages of the toxic dinoflagellate *Alexandrium catenella*, and evaluate the effects of climate change on the timing and location of blooms. This includes detailed mapping of overwintering cysts at 99 stations throughout Puget Sound. The highest surface sediment cyst abundances in 2011 and 2012 were found in Bellingham Bay (north), in bays on the western side of the Main Basin and in Quartermaster Harbor (south) (Figure 35). While cyst distribution patterns were similar for both years, 2012 cyst abundances were approximately half as much as 2011 at most stations. Compared to a 2005 survey, the Bellingham Bay "seed bed" is new, whereas Quartermaster Harbor cyst concentrations have decreased by an order of magnitude. In a related study funded by Washington Sea Grant, cysts from surface sediments at 30 of the 2012 PS-AHAB stations were evaluated for their germination potential with results ranging from 16% to 66% viability. To date, no relationship between cyst viability and cyst appearance has been detected.

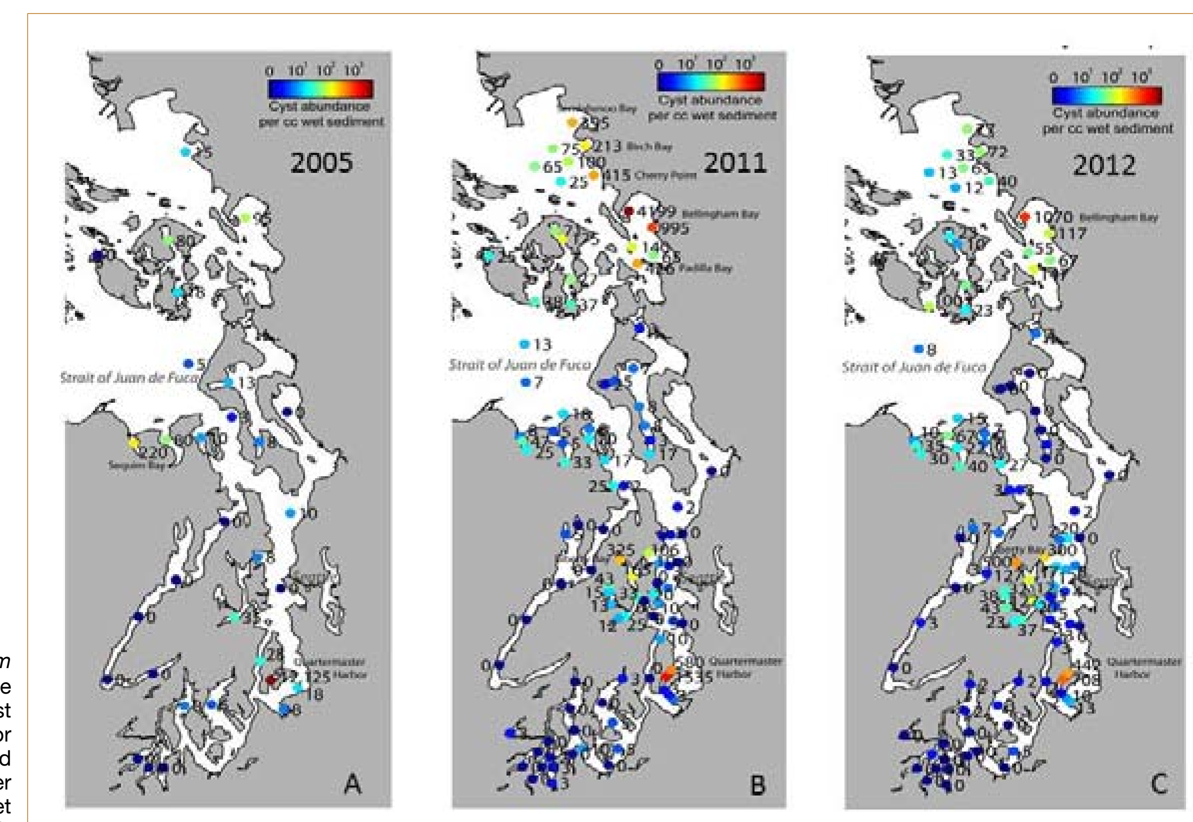


Figure 35. *Alexandrium catenella* surface sediment cyst distribution maps for winter Puget Sound surveys (number of cysts/cc wet sediment).

Biotoxins are produced by certain HABs and can accumulate in shellfish. Health authorities monitor biotoxins in commercial and recreational shellfish to protect humans from illness associated with eating contaminated shellfish. Shellfish are tested for biotoxins that cause paralytic shellfish poisoning (PSP toxins including saxitoxin), amnesic shellfish poisoning (ASP; domoic acid), and diarrhetic shellfish poisoning (DSP toxins including okadaic acid). Harvest areas are closed when toxin levels exceed regulatory limits for human consumption.

C. Biotoxins

Source: Jerry Borchert (jerry.borchert@doh.wa.gov) (WDOH)

In 2012, the Washington State Public Health Laboratory (PHL) analyzed 3,201 shellfish tissue samples for paralytic shellfish poisoning (PSP) toxins. PSP toxins were much higher in 2012 compared to 2011, with the highest value of 10,304 µg/100 g detected in mussels near Kingston in Kitsap County. The Federal Drug Administration (FDA) standard for PSP toxin is 80 µg/100g of shellfish tissue. In 2012, 28 commercial growing areas (23 geoduck clam tracts and 5 general growing areas) and 31 recreational harvest areas were closed due to unsafe levels of PSP toxins. There were nine PSP illnesses reported from people consuming blue mussels from areas that were closed to recreational shellfishing in 2012 (one person on August 14, 2012, from Yukon Harbor, PSP level was 1,621 µg/100 g; one person on September 5, 2012, from the Kingston area, PSP level 10,304 µg/100 g; and a group of seven people on September 22, 2012, from Discovery Bay, PSP level 6,250 µg/100 g).

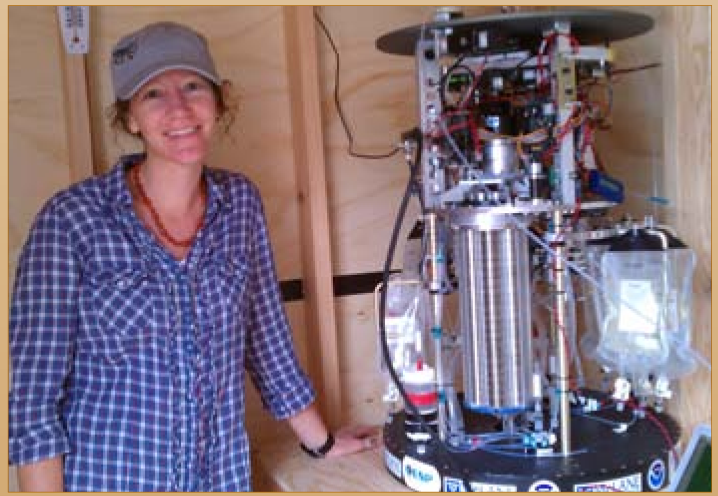
A total of 1,305 samples were analyzed for domoic acid in 2012, with the highest value of 7 parts per million (ppm) detected in blue mussels from Penn Cove on July 22, 2012. There were no commercial or recreational harvest closures due to domoic acid and no ASP illnesses were reported.

In 2012, the WDOH began monitoring for Diarrheic Shellfish Poisoning (DSP) toxins in shellfish in response to the DSP illnesses reported in 2011. The PHL analyzed 903 shellfish samples for DSP toxins from areas in Puget Sound and coastal beaches and bays. The WDOH has adopted the European action level of 16 µg/100 g of shellfish tissue. The highest DSP toxin measured in 2012 was 184 µg/100 g in mussels from Whatcom County. One commercial growing area and 13 recreational areas were closed in 2012 due to DSP toxins. This was the first time that marine biotoxin closures of any kind occurred in areas of Hood Canal (due to DSP) and some areas of Puget Sound were closed to both PSP and DSP at the same time (dual closures). No DSP illnesses were reported.

Photo credit: Vera Trainer

The Environmental Sample Processor

Marine shellfish and finfish are vulnerable to naturally occurring pathogens. Some of these pathogens produce toxins that can accumulate in seafood or cause direct injury. Proactive management of seafood pathogens requires improved sampling collection and analysis. Time lags and travel distances associated with current monitoring can limit sampling frequency. Because a population of microorganisms can achieve explosive numbers within a couple of days, a weekly (or longer) sampling frequency could entirely miss a “bloom” event. The Environmental Sample Processor (ESP), developed by the Monterey Bay Aquarium Research Institute, addresses all of these barriers. The ESP is an autonomous sampling and analysis unit that employs DNA-based technology to detect microorganisms in water samples. It is positioned on site, and relays data by telemetry. The entire process, from sample collection through results delivery, can occur in as little as 3 hours. Flexible sampling frequency can be programmed from daily to weekly or in response to certain environmental triggers (e.g., seawater temperature or salinity), and the ESP can generate information for up to a month or longer before requiring routine maintenance. The ESP uses sensitive and specific molecular assays to produce quantitative results. As an early warning instrument, the ESP will help marine aquaculture move toward proactive resource management.
In the summer of 2012, the Northwest Fisheries Science Center and the Monterey Bay Aquarium Research Institute (inventors of the ESP) deployed an ESP at the University of Washington’s Friday Harbor Laboratory. This was the first time that an ESP had been deployed in the Pacific Northwest. The deployment targeted the fish killing harmful alga *Heterosigma akashiwo*, but other HAB species that contaminate shellfish with biotoxins were also monitored. Daily email notifications were sent to fish farmers, salmon hatchery operators, and shellfish growers. *H. akashiwo* cell abundances approached levels that can kill fish on two separate occasions during the deployment (Figure 36), triggering phone-tree warnings and increased site surveillance at fish farms throughout Puget Sound and in British Columbia and providing the much needed early warning of these harmful blooms (http://www.nmfs.noaa.gov/aquaculture/homepage_stories/08_08_12aquaculture_esp.html).



Dr. Stephanie Moore with the Northwest Fisheries Science Center’s ESP, named “Friday” following the first successful deployment in Friday Harbor in 2012.

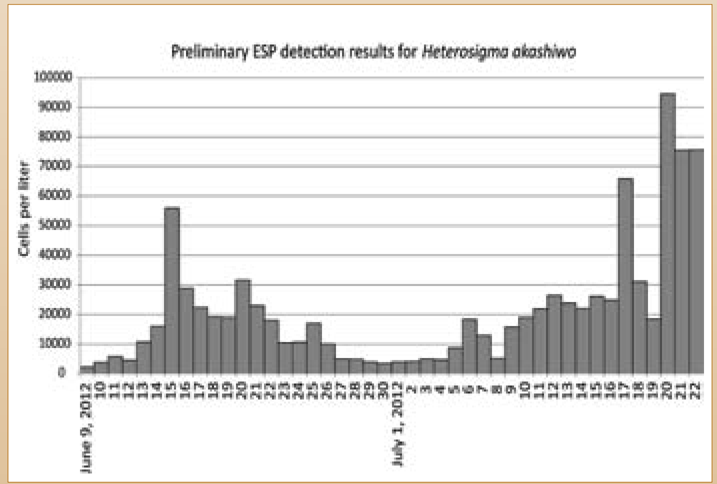


Figure 36: *Heterosigma akashiwo* cell abundance determined from daily measurements by the Environmental Sample Processor from June 9 – July 22, 2012, at the University of Washington’s Friday Harbor Laboratory dock [Moore et al. unpubl.].

Author: Stephanie Moore (NOAA, NWFSC and UCAR)

Bacteria and pathogens

Members of two bacteria groups, coliforms and fecal streptococci, are commonly used as indicators of sewage contamination as they are found in the intestinal tracts of warm-blooded animals (humans, domestic and farm animals, and wildlife). Although they are generally not harmful themselves, they indicate the possible presence of pathogenic (disease-causing) bacteria, viruses, and protozoans. Fecal coliforms are a subset of total coliform bacteria and Enterococci are a subgroup within the fecal streptococcus group.

A. Fecal indicator bacteria

i. Puget Sound recreational beaches

Source: Christopher Clinton (crcl461@ecy.wa.gov) (Ecology & WDOH)

The Beach Environmental Assessment, Communication and Health (BEACH) program is a coordinated effort between the Washington Departments of Health and Ecology. This program coordinates saltwater monitoring at high risk swimming and recreational beaches throughout Puget Sound and Washington's coast and consists of local and county agencies, tribal nations, and volunteers. The goal of the program is to monitor popular, high use beaches for fecal indicator bacteria (enterococcus) and to notify the public when results exceed EPA standards. The program is 100% funded by EPA. In 2012, over 70 beaches were sampled weekly from Memorial Day (May) to Labor Day (September). Figure 37 represents the percent of all monitored Puget Sound beaches meeting the EPA water quality standards for enterococcus (allowing for one exceedance exception). The Puget Sound Partnership uses BEACH data for their Vital Sign indicator and has set a target that all monitored beaches meet human health standards by 2020.

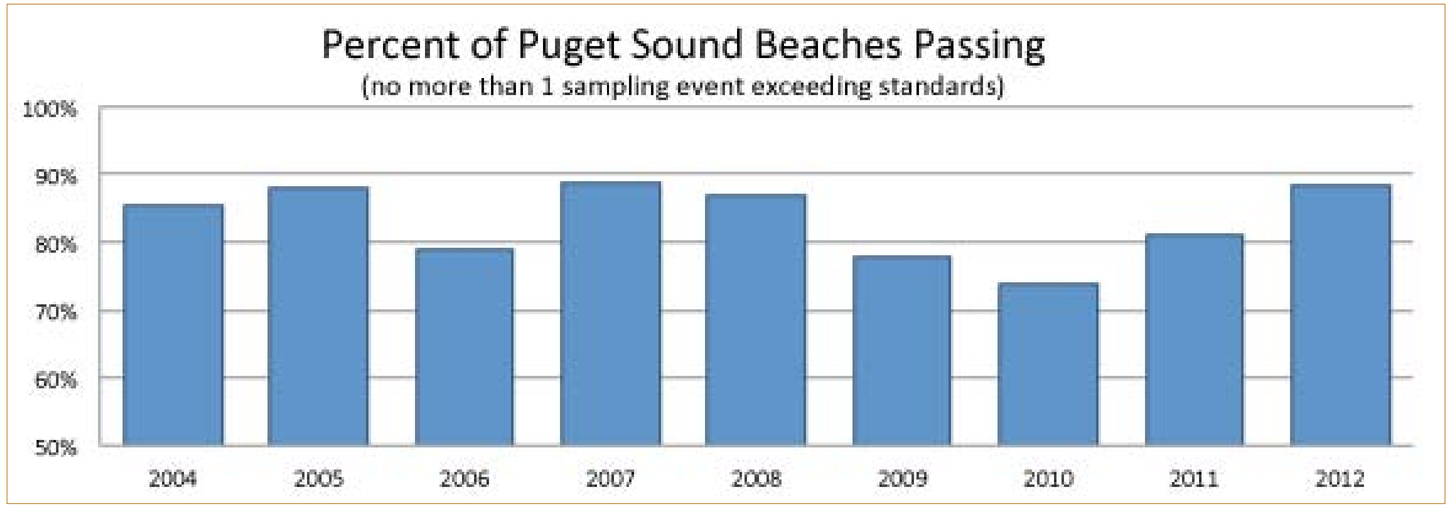


Figure 37. Graph shows the percent of all monitored Puget Sound beaches meeting EPA enterococcus standards.

ii. Main Basin stations

Source: Scott Mickelson (scott.mickelson@kingcounty.gov) (KCDNRP)

King County monitors fecal coliforms at monthly intervals from six ambient and eight outfall stations. Ambient stations are chosen to reflect general, or ambient, environmental conditions, while outfall stations are located at King County wastewater treatment plant and combined sewer overflow (CSO) outfalls. Samples were collected from a depth of 1 m below the surface at all 14 stations. Data were compared to Washington State primary contact marine water quality standards – a geometric mean standard of 14 CFU/100 ml with no more than 10% of the samples used to calculate the geometric mean exceeding 43 CFU/100 ml (peak standard). The geometric mean value reflects the general fecal coliform count at a given station over time, while the peak value is used to determine whether pulses of high fecal coliform counts may be present.

Data collected in 2012 show that all 14 stations passed both the geometric mean and peak standards during all 12 months. This continues a trend seen over many years at King County offshore stations. Out of 168 fecal coliform samples collected during 2012, there was a single excursion beyond the peak standard in a sample collected from a CSO outfall station in Elliott Bay during December 2012.

King County also monitors fecal coliforms in beach water samples collected monthly from 20 marine beaches along the western shoreline of the county as well as on Vashon and Maury Islands. In 2012, 11 of 20 King County beach monitoring stations met the fecal coliform geometric mean standard during all 12 months. Of the 11 stations that met the geometric mean standard, 8 stations also met the peak standard. Eight of 20 stations failed both the geometric mean and peak standards during 2012. Seven of the eight failing stations are located near significant freshwater inputs, either creeks (five stations) or stormwater outfalls (two stations). The eighth station, located at Redondo Beach, has a long history of high fecal coliform counts. The highest number of individual excursions beyond the peak fecal coliform standard occurred in September and October of 2012, in which counts at 8 of 20 stations and 10 of 20 stations, respectively, exceeded the standard. The September sampling event occurred at the end of an extended, two-month period of dry weather. The October sampling event occurred after a 3-day period of rain when over an inch of rainfall was recorded. The percent of King County marine beaches passing the geometric mean and peak standards from 2003-2012 are shown in Figure 38. Freshwater input heavily influences bacteria levels at beach sites; therefore, long-term trends are not readily discernible when sites are aggregated.

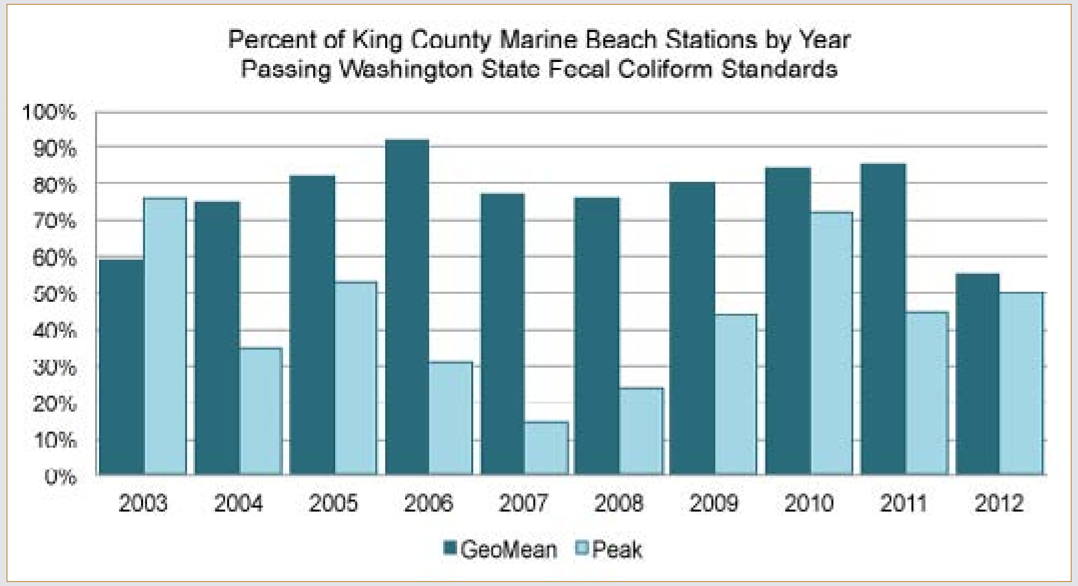


Figure 38. Percent of King County marine beach stations passing fecal coliform standards from 2003-2012.

Vibrio parahaemolyticus (Vp) occurs naturally in the marine environment and is responsible for the majority of seafood-borne illnesses (mainly gastroenteritis), in the U.S, caused by the ingestion of raw or undercooked seafood such as oysters. A large outbreak of Vp-related illnesses occurred in 2006, and in spite of the implementation of stringent post-harvest controls the number of confirmed cases has remained elevated relative to the time period of observation before the 2006 outbreak. Genetic markers for virulent strains of Vp work well in other areas of the U.S., but are not effective in Puget Sound, significantly challenging health authorities.

B. *Vibrio parahaemolyticus*

Source: Richard Lillie and Laura Wigand (laura.wigand@doh.wa.gov) (WDOH)

In Washington State, *Vibrio parahaemolyticus* (*Vp*) related illnesses are controlled by monitoring the populations (total and potentially pathogenic) of these bacteria in oysters from shellfish growing areas. Testing is conducted by the Washington State Department of Health (WDOH). Weather conditions, air, water and oyster tissue temperatures, and salinity are also recorded. In 2012, 262 samples were collected from 27 sites from late May to early October and analyzed for the presence of *Vp*. The highest *tlh* (thermolabile hemolysin) values, a species specific marker of *Vp* that is generally interpreted as an indicator of total *Vp*, were found in Hood Canal sampling sites at >110,000 most probable number (MPN)/g tissue. There were 74 confirmed *Vp*-related illnesses reported in 2012 (66 commercial harvest illnesses and eight recreational harvest illnesses; Figure 39). The majority of illnesses occurred among individuals that consumed raw oysters in July and August, which is consistent with historic illness occurrence. During the *Vibrio* control months for inland water bodies (May-September), eleven shellfish growing areas experienced closures due to high *Vp* levels or the occurrence of *Vp*-related illnesses associated with the areas. Seven of these closures occurred in Puget Sound and the remaining four closures occurred in Hood Canal.

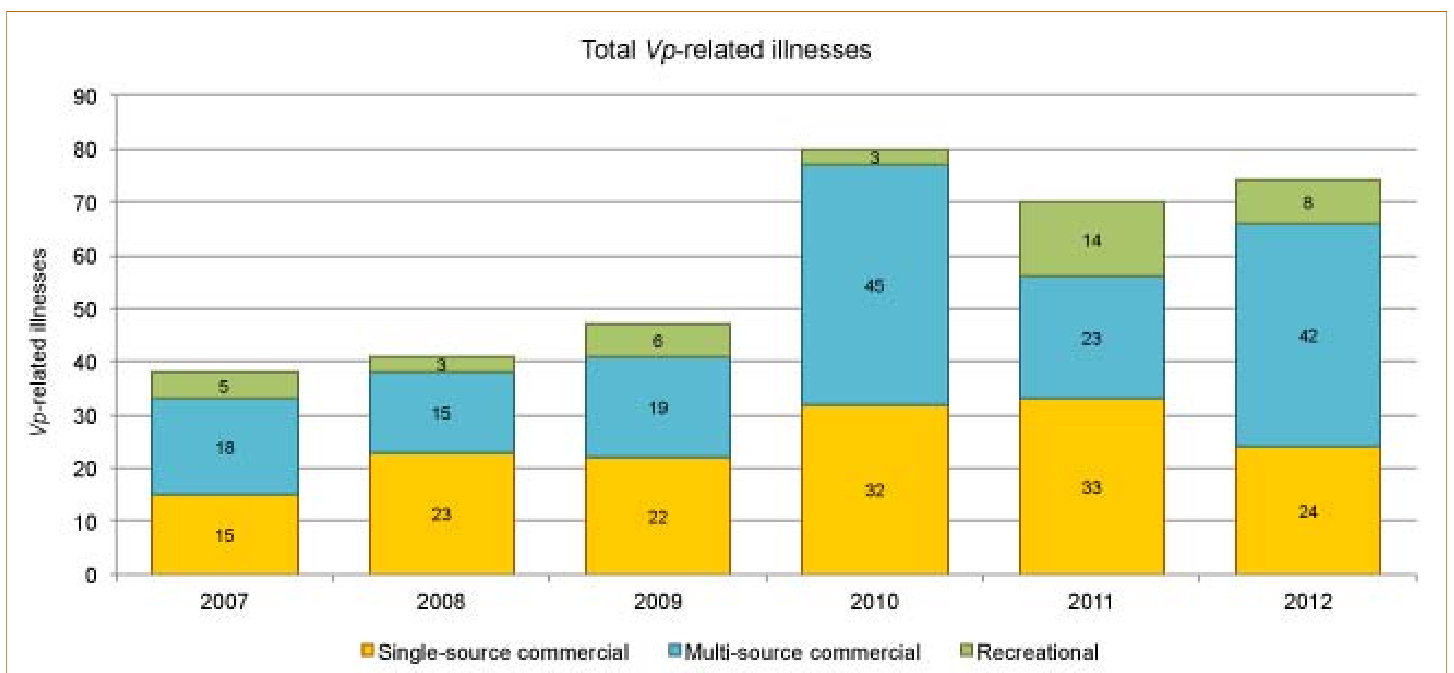


Figure 39. *Vp*-related illnesses for both commercial and recreational harvest areas.

Marine birds

One hundred and seventy-two bird species rely on the Puget Sound/ Salish Sea marine ecosystem either year-round or seasonally. Of the 172 species, 73 are highly dependent upon marine habitat (Gaydos and Pearson 2011). Many marine birds (seabirds such as gulls and auklets, sea ducks such as scoters and mergansers, and shorebirds such as sandpipers and plovers) are at or near the top of the food web and are an important indicator of overall ecosystem health. Marine birds need sufficient and healthy habitat and food to survive.

Protection Island: A refuge for marine birds

Protection Island National Wildlife Refuge is a 364-acre island located near the mouth of Discovery Bay in the Strait of Juan de Fuca. Approximately 70% of the nesting seabirds of Puget Sound and the Strait of Juan de Fuca nest on the island, which includes one of the largest nesting colonies of rhinoceros auklets in the world and the largest nesting colony of glaucous-winged gulls in Washington State. Protection Island contains one of the last two nesting colonies of tufted puffins in the Puget Sound area. Besides seabirds, approximately 1,000 harbor seals depend upon the island for pupping and resting.

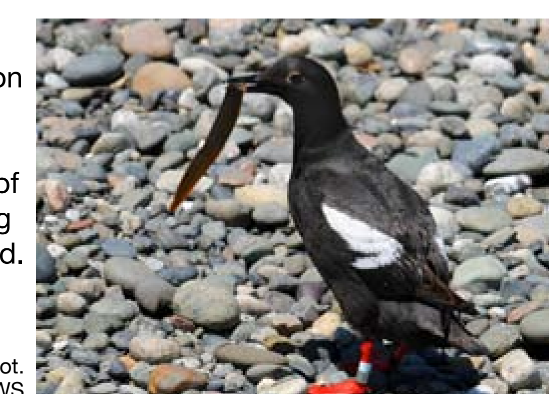
A. Pigeon guillemot – burrow count and breeding success study on Protection Island

Source: Sue Thomas (sue_thomas@fws.gov) (USFWS)

The most recent comprehensive survey found that ~16,000 pigeon guillemots (*Cepphus columba*) inhabit the Washington portion of the Salish Sea (Evenson et al. 2003). Of this total, up to 1,500 can be found on Protection Island, one of the top five sites for pigeon guillemot abundance and a particularly high concentration in the area. However, the proportion of breeding birds on Protection Island is unknown. This data gap has limited the assessment of management actions on breeding guillemots. In response, the first comprehensive survey of active burrows on Protection Island was completed in 2012. Protection Island Refuge staff and volunteers identified 149 burrows with the majority (78%) located within the north and south bluffs or driftwood and below the south bluffs.

Island-wide surveys were conducted the first three weeks in May and burrow counts were conducted in early August when adults returned to the burrows with food deliveries for the chicks. The breeding success study was conducted from mid-July through approximately mid-September after the last chick fledged.

In 2011 and 2012, breeding success (number of chicks fledged/eggs laid) was assessed in a subset of accessible habitats on the island. Preliminary results suggest a lower breeding success in 2012 (25-31%; n=35 nests) compared to that in 2011 (38-45%; n=43 nests), mainly due to a higher incidence of chick mortalities in 2012. There was no evidence of abnormal behavior in adults (based on over 90 hours observing adults provisioning chicks), and necropsies from 2 chicks were inconclusive regarding the cause of mortality. The breeding success rate noted in nest boxes in 2012 is comparable to the low end of the range observed during a 16-year study of breeding success in nest boxes on Protection Island. Other guillemot studies from throughout their range note that breeding success varies considerably among years, and the 2012 Protection Island results fall within published values (Ewins 1993, Ainley and Boekelheide 1990). Results from the continuation of this study in 2013 will provide additional baseline information on the number of active burrows and breeding success on Protection Island.



Pigeon guillemot.
Photo: Peter Davis, USFWS

B. Rhinoceros auklet – populations, diet, and reproduction

Source: Scott Pearson (scott.pearson@dfw.wa.gov) (WDFW), Peter Hodum (University of Puget Sound), Thomas Good (NOAA, NWFSC), and Michael Schrimpf (UW, SAFS)

Spatial and temporal variation in *(1)* population sizes and trends, *(2)* reproduction, and *(3)* diet diversity, composition and quality was assessed for rhinoceros auklets (*Cerorhinca monocerata*) that breed in Washington. These parameters were measured at four island nesting colonies (Destruction Island in the California Current, Protection and Smith Islands in the Salish Sea, and Tatoosh Island at the confluence of these two systems) and compared across two oceanographic regimes (the California Current and Salish Sea). The same parameters were compared between the 1970s and recent years at the four islands.

Between 2006 and 2010, there were 36,152, 1,546, and 6,494 occupied burrows (i.e., active breeding) estimated on Protection and Smith Islands (Salish Sea), and Destruction Island (California Current), respectively (Pearson et al. in press). Estimates for the Salish Sea are 52% greater than those from the 1970s and 1980s, while that for the California Current is 60% less than from 1975. However, some of the estimated changes between time periods could be the result of methodological and analytical differences. To address this, an unbiased and representative sampling approach that optimally allocates samples among islands (Pearson et al. in press) was developed. Overall, reproductive indices (burrow occupancy, hatching and fledging success) were fairly stable in the Salish Sea (Protection Island) and on Tatoosh Island (except for low fledging success in 2007). Destruction Island in the California Current had lower burrow occupancy but higher hatching and fledging success in recent years. Contrary to predictions, auklet population size has apparently increased in recent years relative to the 1970s in the more heavily human impacted ecosystem, the Salish Sea (Protection Island). Rhinoceros auklet chick diet diversity differed dramatically between ecosystems, with higher diversity and variation in the California Current and extremely low diversity and remarkable stability in the Salish Sea. Diet quality as measured by bill load mass did not differ over time, between ecosystems or with changes in oceanographic conditions. Rather than maximizing a particular prey species, auklets appear to be maximizing bill load weight, with the consequence that prey number and total energy content are more variable in most years. Overall, results suggest that the Salish Sea rhinoceros auklet population size has likely increased and diet quality and reproduction are remarkably stable despite increasing anthropogenic stressors on that ecosystem.

Rhinoceros auklet. Photo: Peter Hodum

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Acronyms

APL	Applied Physics Laboratory
BEACH	Beach Environmental Assessment, Communication and Health
CTD	Conductivity Temperature Depth
DO	Dissolved Oxygen
DSP	Diarrheic Shellfish Poisoning
EC	Environment Canada
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ESP	Environmental Sample Processor
HAB	Harmful Algal Bloom
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
KCDNRP	King County Department of Natural Resources and Parks
NANOOS	Northwest Association of Networked Ocean Observing System
NEMO	Northwest Enhanced Moored Observatory
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NPGO	North Pacific Gyre Oscillation
NWFSC	Northwest Fisheries Science Center
ORCA	Oceanic Remote Chemical Analyzer
PDO	Pacific Decadal Oscillation
PFEL	Pacific Fisheries Environmental Laboratory
PHL	Washington State Public Health Laboratory
PMEL	Pacific Marine Environmental Laboratory
PRISM	Puget Sound Regional Synthesis Model
PS Partnership	Puget Sound Partnership
PSEMP	Puget Sound Ecosystem Monitoring Program
PSP	Paralytic Shellfish Poisoning
SAFS	School of Aquatic and Fisheries Sciences
SWFSC	Southwest Fisheries Science Center
TEC	Thermal Energy Content
TJWQP	Tribal Journey Water Quality Project
UCAR	University Corporation for Atmospheric Research
USFWS	United States Fish and Wildlife Service
UW	University of Washington
UWT	University of Washington-Tacoma
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WSG	Washington Sea Grant